Agglutinated and planktonic foraminifera of the Nariva Formation, Central Trinidad, as indicators of its age and paleoenvironment

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ABSTRACT: The Nariva Formation comprises mostly non-calcareous rocks with few calcareous foraminifera, but it is sandwiched geographically in a narrow (<10 km wide) band between the richly calcareous Brasso and Cipero Formations to the north and south respectively. Sixty-one samples were collected from the Nariva Formation at nine transient exposures along a transect trending NNE-SSW across southwestern Central Trinidad. The sparse planktonic foraminiferal assemblages showed the exposures to range in age between Oligocene and early middle Miocene, though many of the samples were of earliest middle Miocene age and coincident with a tectonically-induced transgressive-regressive cycle in the Brasso Formation. The Nariva assemblage at the most southerly exposure, at which the Nariva and Cipero Formations interfingered, was calcareous and of lower bathyal aspect, containing many *Planulina wuellerstorfi*. The assemblage at this exposure did not differ statistically between the two formations, and was thus said to be of "Cipero aspect", although the presence of rare *Elphidium* sp. in the Nariva parts of the exposure attests to some downslope transport.

Recovery from most other exposures was typically small. Richer, predominantly agglutinated assemblages, however, were obtained from the Tarouba Community Centre, Ben Lomond Quarry, Raphael Street, and Tabaquite Heights. The assemblages were of "Brasso aspect", comprising species illustrated previously from the Brasso Formation. Three exposures were sampled at the Raphael Street site, which covered about ten hectares and had been cleared for development. The rocks at this site are patchily but richly stained with hematite and possible manganese derived from hydrothermal activity. Exposure 1 (13 samples) was subdivided into an almost barren interval (Exposure 1a, 8 samples) and an interval containing abundant *Cribrostomoides carapitanus* and *Trochammina* cf. *pacifica* and lesser *Jarvisella karamatensis*, *Arenogaudryina flexilis* and *Glaphyrammina americana* (Exposure 1b, 5 samples). This assemblage is thought to indicate low dissolved oxygen concentrations at middle to lower bathyal paleodepths. That the Brasso Formation was deposited at neritic to shallower middle bathyal paleodepths, while the Cipero Formation at lower bathyal to abyssal depths, demonstrates that the Nariva Formation was deposited on an eastward-facing paleo-slope. Exposures 2 (9 samples) and 3 (5 samples) are dominated by *Simobaculites saundersi* Wilson and Kaminski, n. sp., the walls of which do not incorporate calcareous particles. Many samples yielded large quantities of gypsum that, in view of (a) the paleodepth and (b) the rich planktonic foraminiferal recovery from the adjacent Brasso and Cipero Formations, is thought to reflect syndepositional dissolution of foraminiferal calcium carbonate and its precipitation as calcium sulphate.

Because both the Nariva Formation and the upper Miocene to lower Pliocene Lower Cruse Member (southern Trinidad) yield primarily organically-cemented agglutinated foraminifera, a comparison is made between them. SHE analysis and different mean values of the Assemblage Turnover Index (ATI) shows the community structures in the two formations to differ. Because there is no sign of hydrothermal activity associated with the Lower Cruse Member, despite their taxonomic similarity we conclude that the agglutinated assemblages in the Nariva and Cruse Formations lived in markedly different paleoenvironments.

Keywords: Trinidad, agglutinated foraminifera, hydrothermal activity, assemblage turnover index, SHE analysis, *Simobaculites saundersi* n. sp.

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INTRODUCTION

The Nariva Formation, erected by Wall and Sawkins (1860), underlies much of the Central Range of Trinidad and its southern flanks (Carr-Brown and Frampton 1979; Kugler 1996; text-figures 1, 2). It has, like the upper Miocene to lower Pliocene Lower Cruse Member of the Cruse Formation of southern Trinidad (Batjes 1968; Michelson 1976; Wilson and Vincent 2014), long been famous for yielding large numbers of agglutinated foraminifera (Stainforth 1952). These are as yet incompletely documented. Previous work on the benthic foraminifera has been taxonomic, examining selected species only. Little attention has been paid to the foraminiferal community ecology.

Nor has there been much work on the Nariva's planktonic foraminiferal assemblages, and this paucity of work has led to some disagreement regarding the formation's age. Nevertheless, despite the lack of paleoecological work, the Nariva agglutinated assemblage has been used as an analogue for deep-water, agglutinant-rich deposits elsewhere. Govindan (2004) wrote that many species of benthic foraminifera found in the Nariva and Cruse Formations of South Trinidad occur also in the Miocene to lower Pliocene, middle to lower bathyal Ravva Formation of SE India. He did not, however, state which of the Trinidad formations the Ravva Formation most closely resembles. Likewise, assemblages rich in deep-water, agglutinant foraminifera that include species known from the Nariva Formation can be found in the Miocene of the Gulf of Mexico offshore (Green et al. 2004; Katz et al. 2018), and in the Falcon Basin of Venezuela (Renz 1948; Preece 1999).

The paleogeography of Trinidad during early to earlier middle Miocene times, into which the Nariva Formation must be inserted, comprised a narrow continental shelf (Roure 2007) that extended across large parts of the Caroni Basin and proto-Central Range of northern central Trinidad (Rohr 1990). This lay south and east of the SE advancing Caribbean tectonic plate (Algar and Pindell 1993) (text-figure 1). There were no large and permanent fluvial bodies associated with this shelf, on which were accumulating the calcareous clays of the Brasso Formation (Renz 1948) in clear water (Wilson 2010). The Orinoco River, which is currently the world's fourth largest river in terms of outflow (Hu et al. 2004) and which strongly influenced the late Miocene through recent development of Trinidad (Jones 1998), during the Oligocene and early Miocene flowed northwards into the Caribbean Sea through western Venezuela (Díaz de Gamero 1996), leaving Trinidad unaffected. The late Oligocene to early Miocene Naricual Delta of eastern Venezuela lay several hundred kilometers west of Trinidad and was directed northwards into the eastern Caribbean Sea (Rohr 1990). Nor was the Amazon, sediment-laden water from which is nowadays carried towards Trinidad by the Guiana Current (Aslan et al. 2003; Borstad 1982; Duncan and Schladow 1981; Schott et al. 1998), a factor during the early Miocene (Figueiredo et al. 2009). South of this paleo-shelf and separating Trinidad from northern South America was a deep basin filled with clear water in which the chalky to marly *Globigerina* ooze of the Cipero Formation was accumulating (Carter 1966; Cushman and Stainforth 1945; Rohr 1990; Stainforth 1948). It is not yet clear how the non-calcareous rocks of the Nariva Formation, which geographically lay between the Brasso and Cipero Formations, fit into this paleogeography and geological history. This paper considers this question by examining the planktonic foraminifera and the community paleoecology of the benthic foraminifera of the Nariva Formation. Comparison is made with the almost wholly agglutinated assemblage of the Lower Cruse Formation of southern Trinidad studied by Wilson and Vincent (2014).

THE NARIVA FORMATION; RESULTS FROM PREVIOUS STUDIES
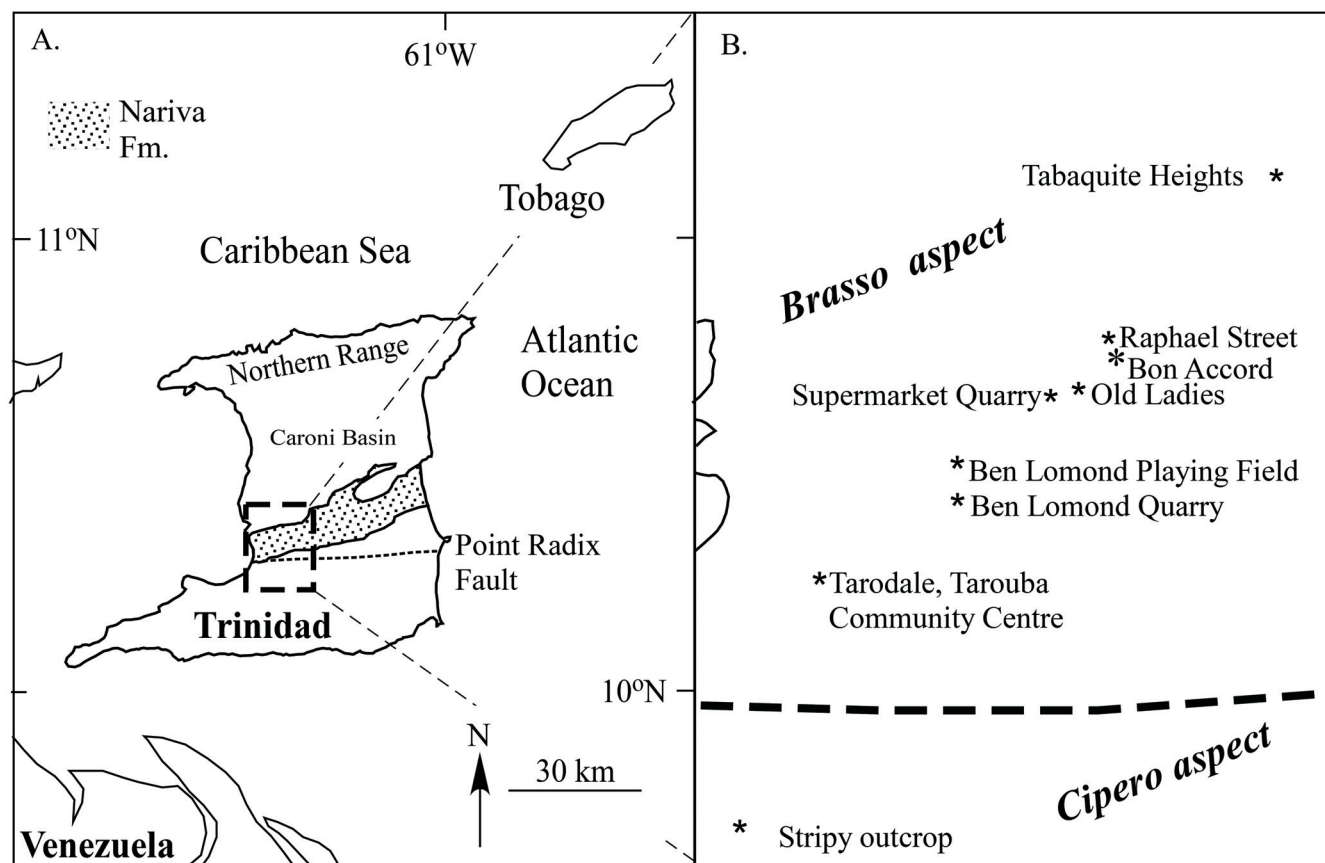
Lithology and Stratigraphy

Due to a paucity of natural outcrops and cored wells, published descriptions of the Nariva Formation are few. Duncan (1868) erected a Nariva Series to cover a band of clays, shales and yellow limestones across the centre of the island. The calcareous

parts of these clays, and the limestones associated with them, have subsequently been grouped to form the neritic to middle bathyal Brasso Formation (Erlich et al. 1993; Renz 1942, 1948; Wilson 2003, 2012), which was deposited on and adjacent to the narrow shelf during early to middle Miocene times. The name 'Nariva Formation' is now restricted to the virtually non-calcareous rocks that trend east–west and crop out in an ~10 km wide belt to the south of the Brasso Formation, in an area termed the Nariva Fold-Thrust Belt (Pindell and Kennan 2007).

Regarding lithology, Pindell and Kennan (2007) concurred with Duncan (1868), referring primarily to "Nariva shales" throughout their text, but occasionally mentioning "Nariva sand fairways". Yet further south, the Nariva Formation interfingers with coeval parts of the calcareous *Globigerina* Ooze of the Cipero Formation of the Southern Basin of Trinidad (Stainforth 1948, 1952).

The relationship between the Nariva and Brasso Formations is as yet unclear, although some authors have thought that the former underlays the latter (text-figure 2). According to Kugler (2001), the 1350 m-thick Nariva Formation ranges in age from the *Globorotalia opima opima* to the *Catapsydrax stainforthi* planktonic foraminiferal Zones of Bolli (1957) (respectively equivalent to Zones P21 and N6 of Blow, 1969), the top of the Nariva Formation in places grading into the calcareous Brasso Formation within the *Catapsydrax dissimilis* Zone (N5). Bolli et al. (1995) thought the Nariva Formation to be Miocene, ranging from the *Globorotalia kugleri* (N4) through *Catapsydrax dissimilis* Zones (N5) (for simplicity, we hereafter use the numbered Zones of Blow (1969) to indicate biostratigraphic ages). In contrast, Pindell et al. (2009, figure 2) showed the Nariva as ranging in age from the Early Oligocene through the early middle Miocene, but gave no evidence to support this and did not state the planktonic foraminiferal zones corresponding to the formation. Blow and Banner (1962) had previously suggested that rocks of early Oligocene age are not found on Trinidad. Pindell et al. (2009, figure 2) wrote that the Nariva in the NW part of the Nariva Fold-Thrust Belt shallowed upwards during early Miocene times into (a) the Cunapo Conglomerate, which was deposited along the northern edge of the paleo-continental shelf, and (b) the Brasso Formation to the south of the Cunapo Conglomerate, which they thought to downlap onto and bury the Nariva. Philip Farfan (unpublished data), however, has recovered the larger foraminifera *Miogypsinoides triangulata* BouDagher-Fadel and Price from the Cunapo Conglomerate at Four Roads Quarry. The specimens, dating from within the late Oligocene to early Miocene planktonic foraminiferal Zones P21 to N5 sensu Blow (1969) (see BouDagher-Fadel and Price 2010), were found interspersed with echinoid and shell fragments in metre-sized clasts of beach rock. This indicates that an area of shallow, high-energy, oxygenated, clear water existed on an Oligo-early Miocene paleo-shelf to the west of the Nariva Fold-Thrust Belt earlier than was suggested by Pindell et al. (2009). Vincent et al. (2014) suggested that the Nariva is of late Oligocene age, and contains a heavy mineral assemblage indicative of an Andean provenance.

Peculiar conditions must have existed to exclude almost all carbonate from the Nariva Formation, given that the deposits from deep-water to the south (the Cipero Formation) and on the shelf to the north (the Brasso Formation) contain abundant carbonate. Renz (1942) described it as being a piedmont facies (flysch) produced by rapid sedimentation resulting from active erosion

TEXT-FIGURE 1
Trinidad and the Nariva Formation. A. Trinidad showing the locations of the Northern Range, Caroni Basin, the areal extent of Nariva Formation outcrop as indicated on the most recent geological map (Saunders 1998), and the suggested site of the Point Radix Fault from Pindell and Kennan (2005). B. Enlarged area of western Central Trinidad, showing sampled sites and areas of "Brasso aspect" and "Cipero aspect" Nariva foraminiferal assemblages. Note that the Stripy Exposure lays south of the area exposing the Nariva Formation as shown by Saunders (1998) and south of the suggested Point Radix Fault.

of a rising, subaerial Northern Range to the north. Suter (1951) thought it to be a shallow-water flysch facies. Stainforth (1968) described it as a wildflysch, it containing gigantic slumped blocks of older rocks. He insisted, however, that the basal conglomerates of the Nariva were the inshore facies of a marine transgression. Higgs (2000) interpreted the Nariva as being deposited on a south-facing submarine slope with mudflows and olistostromes that passed south into deep-sea Cipero basin, although Rohr (1990) suggested that the continental shelf-slope system has undergone considerable rotation during the Neogene, the shelf trending approximately N-S during middle Miocene times (see also Comeau 1991). Higgs (2000) invoked contemporaneous uplift of a proto-Northern Range to the north of Trinidad (= paleo-west) as providing a provenance area in which shale-dominated, deep-sea Cretaceous strata were subjected to subaerial erosion. This he thought would explain (a) the prevalence of clasts attributable to local formations such as the Naparima Hill, (b) the paucity of planktonic foraminifera, this reflecting turbid (muddy) seawaters surrounding a paleo-Northern Range island due to rapid river- and wave erosion of the shale-dominated land, and (c) the southward (distal) disappearance of clasts. In contrast, Pindell and Kennan (2001) suggested from integrated plate kinematic modelling that the Nariva Fold-Thrust Belt was during early to middle Miocene

times located where the leading edge of a Caribbean Accretionary Prism should have been during oblique collision between the Caribbean and South American plates. Pindell and Kennan (2007, figures 33, 34) later provided a 25 Ma palinspastic reconstruction that showed an ENE-trending foredeep axis, fill for which was supplied primarily along-axis rather than from the north. They suggested that the sediment forming the Nariva Formation was therefore derived from the Naricual Delta of eastern Venezuela, ~200 km to the west of the locus of Nariva deposition. Thus, although Kugler (2001) wrote that the consensus of opinion is that the Nariva Formation represents a marine slope environment, and not a neritic one, clearly there is no agreement regarding either age or paleoenvironment among the published papers. This paper addresses these matters.

A study of the benthic foraminiferal biofacies in the Nariva Formation might also have some relevance to plate tectonic studies. Pindell and Kennan (2007, figure 5) suggested that a major transform fault (the Point Radix Fault) of post 10 Ma age extends WSW from Point Radix, eastern Trinidad, and lays near the southern margin of the Nariva Fold-Thrust Belt as mapped by Saunders (1998). Although in our fieldwork one of us (CH) found a fault at Point Radix, displacement across it was noted to be a metre only. Should a fault at Point Radix have undergone

major movement during the last 10 Ma, then one would expect there to be a major change in Nariva biofacies across it. This paper investigates this possibility.

Benthic foraminifera

Brönnimann (1951) described the alveolar genera *Guppyella*, *Alveovalvulina* and *Discamminoides* from Upper Miocene deposits of the Lower Cruse Formation but noted that "morphologically related forms are also known from the clays of the Oligocene Nariva and Cipero formations." Brönnimann (1953) recorded the following species from the Nariva Formation: *Gravellina narivaensis* Brönnimann 1953, *Alveovalvulinella pozonensis* (Cushman and Renz 1941), *Valvulina flexilis* Cushman and Renz, 1941 (herein placed in the genus *Arenogaudryina*), and *Haplophragmoides narivaensis* Brönnimann, 1953. Bolli et al. (1995) described the Nariva assemblage as including some characteristic alveolar, deep water species. Kugler (2001) listed *A. pozonensis*, *G. narivaensis*, *H. narivaensis*, *H.* aff. *H. narivaensis* and *A. flexilis* from the Nariva Formation, and noted that the assemblage recorded by Blow (1959) from the lower Miocene San Lorenzo Formation of western Venezuela, which includes *Cyclammina cancellata* Brady, *Alveophragmium* spp. and robust *Haplophragmoides* spp., resembles that of the Nariva Formation. Stainforth (1952) postulated that neither depth, temperature nor salinity were major factors in the development of the agglutinated Nariva foraminiferal assemblages, and tentatively suggested that turbidity was the main controlling ecologic factor, turbid water at the sea surface disrupting the photosynthesis vital to the existence of some calcareous organisms and their algal symbionts. He did not, however, state from where this turbid surface water came.

GENERAL ASPECTS OF THE STUDIED SITES

The Nariva Formation is patchily exposed throughout western Central Trinidad, where we visited nine sites, all man made, along a NE-SW transect (text-figure 1B, Table 1). The area covered by each site ranged from a few square decimetres (the Stripy Exposure near Philippine) to about ten hectares (Raphael Street).

The Stripy Exposure, situated along the north-bound Uriah Butler Highway near the Debe interchange, consisted of interbedded Nariva and Cipero Formation (text-figure 3A). The rocks occurred as alternating bands up to ~2 m thick of cream-brown Cipero mudstone and red-brown to medium grey Nariva mudstone.

Our observations at exposures elsewhere indicate that the Nariva Formation comprises virtually non-calcareous to completely non-calcareous, dark-grey to red-brown, fine- to coarse-grained clastic rocks (text-figure 3B, C). The mudstones are admixed with turbidites and debris flow deposits containing lithic fragments of granule and larger size, some olistoliths being hundreds of metres across (Kugler 2001). These fragments occasionally form conglomeratic beds up to 1 m think. The grain size of the coarser fraction decreases southwestwards across Central Trinidad, the lithic fragments being coarsest at Raphael Street and absent at Ben Lomond Quarry and the Stripy Exposure. The exposure at Ben Lomond Quarry is, however, adjacent to a single, possible olistolithic or fault-bounded outcrop of the Middle Cretaceous Naparima Hill Formation about 40 m across. Some of the pebbles at Raphael Street are of Naparima Hill Formation, are rounded, and have shiny, pol-

ished surfaces reminiscent of previously unreported desert varnish, reflecting a provenance in an arid hinterland. A few cobbles have borings reminiscent of those produced by the bivalve *Lithophaga*, proving the presence of a stony paleo-shoreline. Some horizons are rich in gypsum that Guppy (1900) thought had been derived from calcareous foraminifera, the calcium carbonate from the tests having been dissolved and re-precipitated as calcium sulphate. Such a suggestion is supported by more recent field and laboratory work. There are at Raphael Street and Tabaquite Heights patches of the formation several square decimetres in extent that are stained bright red with what are assumed to be hematite and manganese. Synsedimentary slumping and folding being frequent, an attempt was made to sample from synsedimentarily undisturbed sections of the exposures.

The exposure at Raphael Street was particularly extensive and complex. Preparatory work in 2014 for housing here scraped the soil from an area of the Nariva Formation. A road system subdividing the development had been installed before we visited the site (text-figure 4). Only one of Trinidad's monsoonal rainy seasons had occurred since clearing, but the area was already largely overgrown with coarse grass ('elephant grass') and had in places been eroded into gullies up to 1 m deep. Of the better exposed areas, three exposures showing little synsedimentary deformation and no evidence of turbidites were sampled.

MATERIALS AND METHODS

Sample Collection

Samples were taken by excavating to a depth of 15 cm to minimise specimen loss due to weathering. Thirteen samples were collected from the most southwesterly Stripy Exposure, both the Cipero and Nariva Formation lithologies being sampled to allow comparison. The Ben Lomond Quarry through Bon Accord exposures were represented by between one and four samples each, while six samples were recovered from the most northeasterly exposure at Tabaquite Heights. Where more than one sample was taken from a site, these were collected at 1 m intervals.

Exposure 1 at Raphael Street lay on the northern side of an installed roadway at 10°20'22.51"N, 61°21'48.93"W. Occasional horizons richer in cobbles within the succession of sandy mudstones here indicated subvertical bedding trending ESE–WNW. Twelve samples (BWPF-40 to BWPF-52, exposure base and top respectively) were taken at 1 m stratigraphic intervals from Exposure 1. Exposure 2 lay on the southern side of Raphael Street, stratigraphically ~30 m above Exposure 1. Nine samples (BWPF-53 through BWPF-61) were recovered from this exposure at 1 m intervals. Bedding at Exposures 1 and 2 was parallel, suggesting that the samples from these represent a conformable section. Exposure 3 lay 300 m WNW of Exposure 1. Subvertical bedding here strikes 034°. Five samples (BWPF-62 through BWPF-66) were taken stratigraphically 1.5 m apart from this exposure.

Sample Preparation and Analysis

In the laboratory, 40 g (most exposures) or 50 g (Raphael Street) of each sample were soaked in water for 24 hours, boiled, and then washed over a 63 μm sieve to remove silt and clay. The indurated sample BWPF-49 from Raphael Street required brief freezing while wet to disaggregate completely. The dried residues were sieved over a 105 ìm mesh. An attempt was made to split the >105 μm fractions using a microsplitter into aliquots

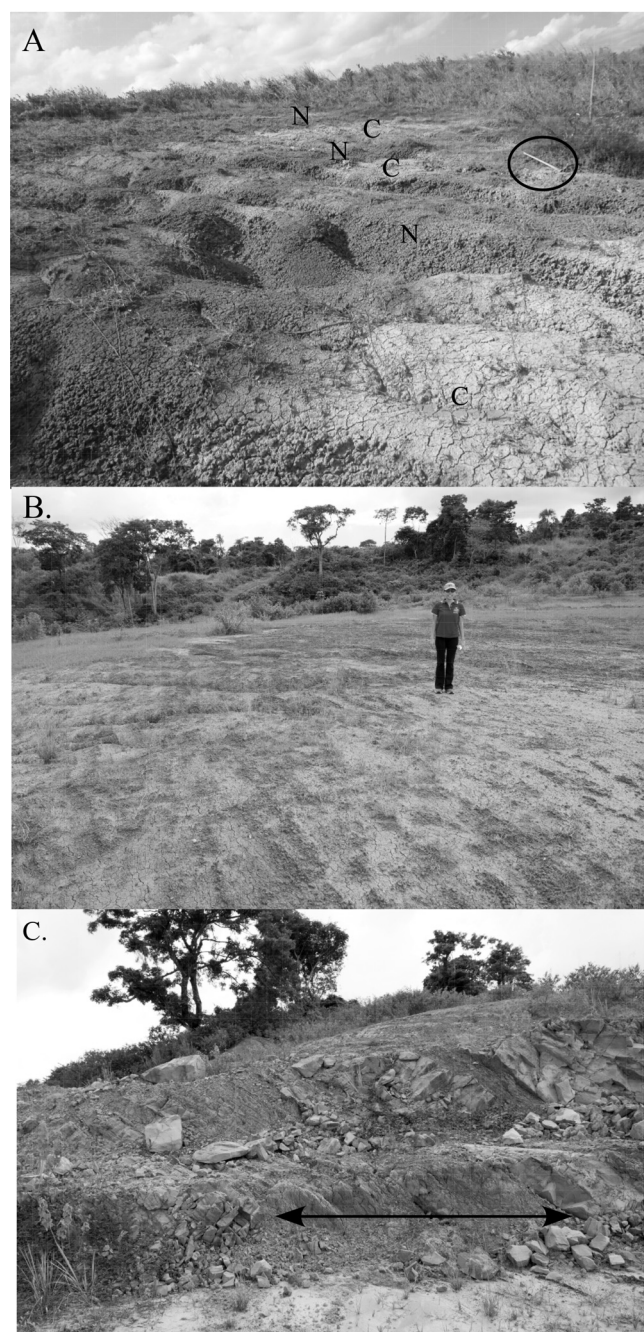| Planktonic foraminiferal Zones (after Bolli, 1957)		Blow (1969)	Kugler (2001)		This paper	
			Central Trinidad	Southern Trinidad	Central Trinidad	Southern Trinidad
Miocene	*Globorotalia fohsi robusta*	N12	Brasso Formation	Cipero Formation	Brasso Formation / Nariva Formation	Cipero Formation
	Globorotalia fohsi lobata	N11				
	Globorotalia fohsi fohsi	N10				
	Globorotalia fohsi peripheroronda	N9				
	Praeorbulina glomerosa	N8				
	Globigerinatella insueta	N7				
	Catapsydrax stainforthi	N6				
	Catapsydrax dissimilis	N5				
	Globorotalia kugleri	N4	**Nariva Formation**			
Oligocene	*Globigerina ciperoensis*	P22				
	Globorotalia opima opima	P21				
	Globigerina ampliapertura	P19/20	?	?	?	

TEXT-FIGURE 2
Upper Oligocene to Middle Miocene stratigraphy of central and southern Trinidad as suggested by Kugler (2001) and this paper. The stippled area represents the Cunapo Conglomerate.

with ~200 specimens. Many samples did not yield this many specimens and were picked in their entirety. Specimens were sorted into species and the benthic species identified using illustrations by Cushman (1918, 1920, 1922), Renz (1948), Brönnimann (1951, 1953), Barker (1960) and Bolli et al. (1995). The planktonic foraminifera encountered were identified using illustrations by Kennett and Srinivasan (1983), and their publication used to determine stratigraphic ranges. Chi squared with 1 degree of freedom was used to compare the number of foraminifera per gram at the Stripy Exposure, while analysis of variance (ANOVA) was used to examine the mean number of specimens per sample in the three exposures at Raphael Street.

Bender (1995) noted that most modern agglutinating foraminifera have organically cemented tests. The remainder, including shallow water *Valvulina oviedoiana*, use calcareous cement (see also Mancin, 2001), as does *Textularia saggitula* Defrance,

TEXT-FIGURE 3
Selected exposures of the Nariva Formation. A. The Stripy Exposure near Philippine, on which N and C indicate the interfingering Nariva and Cipero Formations respectively. The pickaxe, circled, is 1 m long. B. An area of slumped and hematite-stained Nariva Formation at the Raphael Street site, indicating the highly variable grain size. C. interbedded silty shales and turbidites at the Raphael Street site. The silty interval (arrowed), ~3 m thick, is strongly stained with hematite.

the type species of this genus (Murray 2003). Specimens of each of the most abundant species in the Nariva Formation were tested for solubility in dilute hydrochloric acid. The *Valvulina flexilis* sensu Cushman and Renz were found to be acid insoluble, so they are here ascribed to the genus *Arenogaudryina*.

Also recorded were acid insoluble specimens with a *Textularia* morphology. These evidently do no belong to this genus, and are here referred to as "*Textularia*" spp. Kaminski et al. (1995) recorded similar acid insoluble "*Textularia*" in suboxic basins off Southern California.

Diversity at Raphael Street was compared between the samples and exposures using species rarefaction and the Shannon function H [$= -\Sigma p_i \cdot \ln(p_i)$, where p_i is the proportional abundance of the *i*th species. For details, see Magurran (2004) and Hayek and Buzas (2010). Calculations were made using the PAST paleontological freeware of Hammer et al. (2001) version 3.0.

To assess the rate of assemblage turnover between samples within each Raphael Street exposure, the sample-wise assemblage turnover index (ATI$_s$) of Hayek and Wilson (2013), Wilson and Hayek (2014a, b) and Wilson et al. (2014) was calculated from the expression

$$ATI_s = \sum |p_{i2} - p_{i1}|$$

in which ATI$_s$ is the between-sample assemblage turnover, and p_{i1} and p_{i2} are the proportional abundances of the *i*th species, i=1 2, 3,…,S, in the lower and upper samples. ATI$_s$ gives the proportion of assemblage turnover or change between adjacent samples using the vectors of proportional abundances. The mean ($\bar{x}$) and standard deviation (sd) of values of ATI$_s$ were calculated over the entire set of samples and then between the samples within each exposure. Values of ATI$_s$ are normally distributed, as is expected of a statistic that is a sum. Hayek and Wilson (2013) used values of ATI$_s$ exceeding a contol limit of ($\bar{x}$ + sd) to indicate the positions of relative major assemblage turnovers. Here we use these same control limits to indicate points of major turnover within each exposure. However, as we do not know the stratigraphic relationships between the exposures in this complexly folded and faulted terrane, no attempt is made to compute the values of ATI$_s$ between them.

Comparison with the Lower Cruse Member

Wilson and Vincent (2014) examined the predominantly agglutinated foraminiferal assemblage in the Lower Cruse Member (Upper Miocene) of southern Trinidad. They suggested that the dominance of *Spirosigmoilinella compressa* indicates lower bathyal to abyssal paleodepths, but also recorded low values of the Shannon Function H typical of shallower water. Subdominant *Haplophragmoides carinatus* indicated dysoxic conditions. They also recorded rare (1.8% of total recovery) *Arenogaudryina flexilis* (as *Valvulina flexilis*). However, these authors did not record gypsum. Jones (1998) suggested the paucity of calcareous matter in the Lower Cruse might be penecontemporaneous, due to elimination from surface water of marine phytoplankton used as food by some planktonic and deep-water benthic calcareous foraminifera, or possibly due to salinity stratification, which would reduce circulation and oxygenation of bottom waters, allowing dissolution of calcite by acids released from decaying organic matter. Here we compare the assemblage in the Nariva Formation and Lower Cruse Member in an attempt to determine which of these explanations is more likely.

SHE analysis (Buzas and Hayek 2011; Hayek and Buzas 1997, 2010; Wilson 2008b) was used to compare patterns in species richness *S*, the Shannon Function H and the Equitability Index E ($= e^H/S$) over all samples from within the Nariva Formation at Raphael Street and the Lower Cruse Member, using both the ag-

glutinated and calcareous foraminifera. Four samples taken from the Nariva Formation at Raphael Street were barren. The interior samples (BWPF-45/46) were included and two exterior ones (BWPF-40/ 41) excluded from analysis. Samples were accumulated in order of the numbered Exposures 1a, 2 and 3 and over all samples.

RESULTS

The Stripy Exposure

The recovery of the planktonic foraminifera *Globorotalia fohsi fohsi* and *Sphaeroidinellopsis kochi* indicate this exposure to be of middle Miocene (N12) age. The benthic foraminiferal assemblages throughout were of Cipero aspect, consisting primarily of calcareous specimens identified using Cushman and Stainforth (1945) (see Supplementary Data 1). The mean recovery of benthic foraminifera from the cream-brown, Cipero lithology was 74 foraminifera per 40 grams (sd = 65.3; 1.85 specimens/g), while that from the red-brown to grey lithology was 58.4 (sd = 83.9; 1.46 specimens/g). Chi squared with 1 degree of freedom had a value of 3.412 and p = 0.065, so there is no statistically significant difference in the number of foraminifera recovered from the two lithologies at the p < 0.05 level. Rare *Elphidium* sp. were recovered from the Nariva lithology, but not from the Cipero. The Nariva and Cipero Formations have traditionally been seen as having distinct foraminiferal assemblages, that in the Nariva being agglutinated. There was, however, no difference in the assemblages between the two lithologies at this exposure.

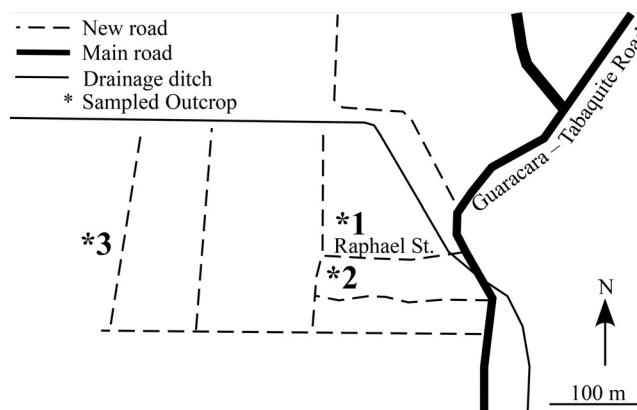### Tarodale, Tarouba Community Centre

Two samples were taken from this exposure, which was the most southerly in the area mapped by Saunders (1998) as being underlain by the Nariva Formation. They yielded much gypsum and acid-insoluble agglutinated foraminifera (*Trochammina* cf. *pacifica*, *Haplophragmoides* spp., *Reticulophragmium acutidorsatum* and *Nothia* spp.) (Supplementary Data 2). Only one specimen of calcareous foraminifera, the planktonic species *Globorotalia obesa*, was recovered. This species is of little biostratigraphic use, it having a wide stratigraphic range (upper Oligocene to Holocene).

Ben Lomond Quarry

One of the two samples examined from this exposure yielded *Globigerina ciperoensis ciperoensis*, but neither yielded specimens of *Globorotalia*. This is thought to indicate an Oligocene age. The remaining planktonic foraminifera were too small to be identified to species level, but planktonic specimens formed 7–13% of the total foraminiferal recovery. The benthic foraminiferal assemblage comprised primarily organically-cemented agglutinated specimens (95–98% of benthic foraminifera), with sparse calcareous walled species. No calcareous-cemented agglutinants were recorded. The benthic assemblage was dominated by *Trochammina* cf. *pacifica* with lesser *Trochammina* sp. 2.

Ben Lomond Playing Field through Bon Accord

Recovery from these exposures, which did not show the pronounced hematite staining of rocks at Tabaquite Heights and Raphael Street, was sparse. The occurrence of *Globorotalia fohsi peripheroacuta* at Ben Lomond Playing Field and the Supermarket Quarry indicates an early middle Miocene age (N10–N11), although the former contained reworked upper Eocene material (*Turborotalia cerroazulensis cocoaensis*). The
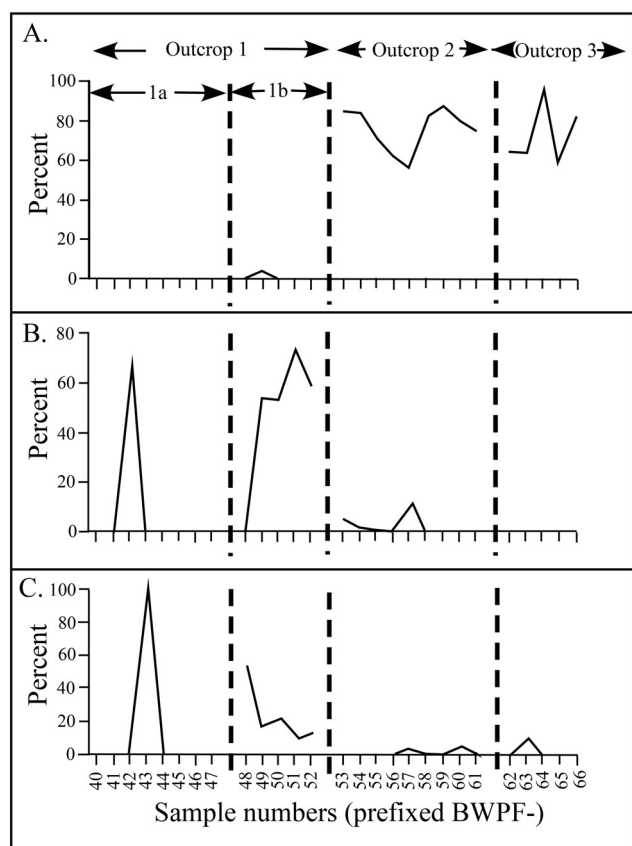

TEXT-FIGURE 4
The sampled exposures at Raphael Street.

planktonic foraminiferal specimens from these sites were white and so did not show any evidence of diagenetic change. Benthic foraminiferal recovery ranged between 0–24 specimens per sample and was dominated by organically-cemented agglutinants.

Raphael Street

A total of 2,991 benthic and four indeterminate planktonic foraminifera were picked from the 27 Nariva samples taken here (Supplementary Data 2). We discuss the benthic assemblages only. Five calcareous benthic foraminifera (0.17% of the benthic assemblage) were recovered from the 27 samples, belonging to *Allomorphina trigona* Reuss 1850, *Bulimina pupoides* d'Orbigny 1846 and *Chilostomella oolina* Schwager, 1878, all stained dark brown. Just nine samples yielded >200 benthic foraminifera, although sample BWPF-58 yielded 199 specimens. The mean yield per sample was overall 111 specimens (sd = 98.7 specimens). Samples BWPF-40 through BWPF-47 (Exposure 1) presented much fine sand and together yielded only 19 specimens, with four of the eight samples being barren. These are henceforth grouped as Exposure 1a. The mean recovery per sample from the upper part of Exposure 1 (samples BWPF-48 through BWPF-52, hereafter termed Exposure 1b) was 227 specimens, for Exposure 2 was 175 specimens, and for Exposure 3 was 54 specimens per sample. Some extremely rich samples, principally from Exposure 1b, were not picked in their entirety, while all samples yielding <200 specimens were picked clean. ANOVA shows that there was a difference in the mean recovery between the exposures ($F_{2,16}$ = 17.3, p = 0.0001).

About 1.8% of the recovery comprised unidentifiable fragments. A total of 34 species or taxa in open nomenclature were distinguished among the remaining agglutinated foraminifera. Of the total recovery, 47% comprised *Simobaculites saundersi* n. sp., which occurred rarely at Exposure 1b but dominated at Exposures 2 and 3 (text-figure 5). Most specimens of *Simobaculites saundersi* were juveniles that lacked the uniserial stage, but a few adult specimens were found. Subdominant species comprised *Cribrostomoides carapitanus* (19% of total recovery) and *Trochammina* cf. *pacifica* (10% of total recovery). The specimens of both *Cribrostomoides* and *Trochammina* are invariably crushed, and only rare specimens of the former were

TEXT-FIGURE 5
Percentage abundances of selected species at the Raphael Street exposures. A. *Simobaculites saundersi* n.sp. B. *Cribrostomoides carapitanus,* C. *Trochammina* cf. *pacifica.*

recovered that show the apertures. *Cribrostomoides carapitanus* and *T.* cf. *pacifica* were largely restricted to Exposure 1b. Other species forming >1% of the total recovery are "*Textularia*" sp. 1 (4% of total recovery), "*Textularia*" sp. 2 (1%), *Arenogaudryina flexilis* (3%), *Jarvisella karamatenis* Brönnimann, 1953 (2%), *Alveovalvulina suteri* (1%), *Reophax scorpiurus* de Montfort, 1808 (1%), and *Nothia* spp. (2%). Of these, *A. suteri* and *A. flexilis* were recovered primarily from Exposure 1a, *J. karamatensis* from Exposure 1b,"*Textularia*" sp. 1 from Exposure 2, and "*Textularia*" sp. 2 from Exposure 3. Only five species with labyrinthic wall structures, collectively forming ~3% of the total recovery, were recorded: *A. suteri*, *Alveovalvulinella pozonensis* (Cushman and Renz 1941) *Reticulophragmium acutidorsatum* (von Hantken 1868), *Cyclammina placenta* (Reuss 1851), and *Jarvisella karamatensis*.

Species richness S of a sample being a function of the number of specimens N picked (Buzas et al., 1977), the highly variable values of N (range 0–256) precluded direct comparison of S between exposures. Comparison was made, therefore, using rarefied species richness S_r at 60 specimens for those samples with >60 specimens (text-figure 6A). S_r at Exposure 1b (five samples) ranged from 5.7–8.5 species per sample ($\bar{x} = 7.2$, sd = 1.4). For Exposure 2 (nine samples), S_r ranged from 3.9–7.0 species per sample ($\bar{x} = 5.3$, sd= 1.0). For Exposure 3 (two samples), S_r was 3.2 and 5.0 species per sample ($\bar{x} = 4.1$, sd = 1.3). Normal

quantile plot - tests for non-normality showed that values of S_r for Exposure 1b ($r_{obs} = 0.91$, $r_{crit} = 0.88$) and Exposure 2 ($r_{obs} = 0.98$, $r_{crit} = 0.91$) were normally distributed at p = 0.05. Hartley's F_{max} test for equality of variance showed that the variances for Exposures 1b and 2 did not differ significantly ($F_{max,obs} = 1.68$, $F_{max,crit} = 9.6$, df = 4). ANOVA and Tukey's *post hoc* Q test were therefore used to compare S_r between exposures 1b, 2 and 3. ANOVA indicates that there is a significant difference in the mean values of S_r between at least two of the exposures ($F_{2.16} = 6.395$, p = 0.012). Tukey's test showed that the mean S_r for Exposure 3, which was the smallest, was significantly different from that for Exposure 1b (Q = 5.05, p = 0.009), but this test did not reveal any other significant differences. The Shannon Index H across all samples ranged between 0.26–1.51.

The sample-wise assemblage turnover index (ATI_s) was calculated within the exposures using all samples from Exposures 1b, 2 and 3. Across all exposures it ranged between 0.24–0.76 ($\bar{x} = 0.52$, sd = 0.28), with the maximum and minimum within Exposures 1b and 3, respectively (text-figure 6B). When all three exposures are considered, only the ATIs between samples BWPF-48/49 exceeded ($\bar{x} + sd$). This was due to the higher percentage abundances in sample BWPF-48 of *Jarvisella karamatensis* (20% of that sample) and *Trochammina* cf. *pacifica* (55.0%) compared to BWPF-49. The dominant species in BWPF-49 (*Cribrostomoides carapitanus*; 53.3% of that sample) was not recovered from BWPF-48.

The mean ATI_s within all Exposure 1b samples was 0.63. The high ATI_s of 1.32 between samples BWPF-48/49 reflects the largest change in assemblage between any two adjacent samples at any of the exposures. When the lowest sample, BWPF-48, is excluded, mean ATI_s between the remaining four samples from Exposure 1b is 0.39 (sd = 0.15). Within Exposure 2, ATI_s ranges from 0.27 - 0.72 ($\bar{x} = 0.39$, sd = 0.16). The ATI_s between samples BWPF-57/58 exceeded ($\bar{x}+sd$) for this exposure, indicating a more marked change in the assemblage between these two samples than between any other adjacent pairs. The percentage abundance of *Simobaculites saundersi* n.sp. rose from 55.7% in BWPF-57 to 80.9% in BWPF-58, while that of *Cribrostomoides carapitanus* fell from 10.8% in BWPF-57 to 1.0% in BWPF-58. Within Exposure 3, ATI_s ranges from 0.48 - 0.76 ($\bar{x} = 0.66$, sd = 0.13) and no value of ATI_s exceeded ($\bar{x} + sd$).

The number of readings of ATI_s obtained from each of the exposures varied widely, from three in the upper part of Exposure 1b to eight from Exposure 2. For these small sizes we used both ANOVA and Krustkal-Wallis to compare ATI_s between the exposures. Both means and medians were barely significantly different, with H (χ^2) = 6.154, p = 0.046. Median ATI_s at Exposure 3 (0.70) exceeded that at Exposure 2 (0.33) and that between the uppermost three values of ATI_s at Exposure 1b (0.42).

Two agglutinated foraminiferal species reported by Bender (1995) with organic cements were recovered from the Nariva: *Saccammina sphaerica* Brady 1871, *Reophax scorpiurus*. Bender (1995) also noted organic cements in *Cyclammina* spp. and *Haplophragmoides* spp. Eight species of agglutinated foraminifera recovered from the Nariva Formation were represented by singletons and were not tested for acid solubility. All other agglutinated species proved to be insoluble in dilute hydrochloric acid. That the walls in the untested singletons appear comparable to those in the tested species suggests that the entire agglutinated assemblage is acid insoluble.

Tabaquite Heights

The samples from this exposure yielded rare planktonic foraminifera, including *Globorotalia scitula* and *Hastigerina praesiphonifera*, the overlapping biostratigraphic ages of which suggest an early middle Miocene age (N9–N13) perhaps comparable with that of the Ben Lomond Playing Field through Bon Accord exposures. Both the planktonic and calcareous benthic (*Globobulimina pacifica*) foraminifera were stained deep brown. Benthic foraminiferal recovery was sparse to good (14–138 specimens per sample), with abundant *Alveovalvulinella pozonensis*.
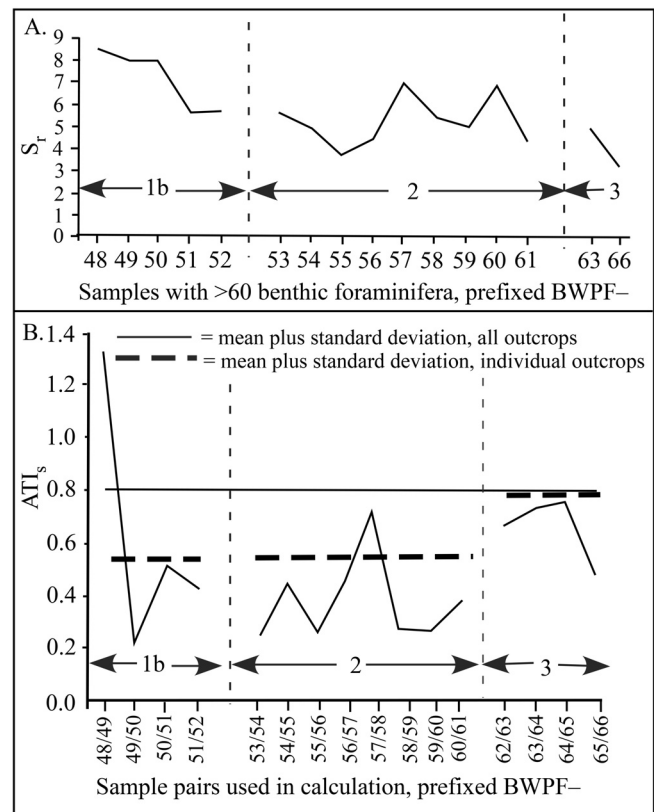
Comparison between the Raphael Street Assemblage and that in the Lower Cruse Member

Over all the samples taken from the Nariva Formation at Raphael Street, benthic N = 2,998 (including calcareous specimens), S = 22, H = 1.68 and E = 0.25. In the Lower Cruse Member, over all samples, benthic N = 2,938 (including calcareous specimens), S = 33, H = 2.30 and E = 0.30. The comparable values of N show that S is greater in the Lower Cruse Member than in the Nariva Formation. The ATI_s within the Lower Cruse Member ranges from 0.43–1.46 ($\bar{x}$ = 0.87).

From SHE analysis, the linear regression of H *vs.* lnN within the Nariva Formation is not significant, yielding the equation H = 0.079lnN + 1.25. In contrast, the linear regression of H *vs.* lnN within the Lower Cruse Member is significant with F = 736.23, p < 0.00001 and the equation H = 0.343lnN–0.383. This shows that the community structures of benthic foraminifera within the Nariva Formation and Lower Cruse Members differ greatly. This is supported by the linear regressions for lnS *vs.* lnN and lnE *vs.* lnN for the Nariva Formation, both of which are significant (lnS = 0.315lnN + 1.08; lnE = –0.236lnN + 0.177, p < 0.00001.) but differ in both intercept and slope from those linear regressions for the Lower Cruse Member (lnS = 0.460lnN + 0.097; lnE = –0.117lnN–0.236, p < 0.00001). A test of the difference in the slopes of lnE *vs.* lnN was significant. In summary, diversity being composed of both richness and evenness, the diversities in these two lithostratgraphic units were significantly different. The diversity H regression showed that H was stable over the entire set of Nariva exposures with a non-significant slope, while the slope for H from Lower Cruse Member was significant.

DISCUSSION

The recovered planktonic foraminifera suggest that the Nariva Formation is Oligocene to middle Miocene in age, which is in accordance with the age suggested by Pindell and Kennan (2009). However, some of the exposures examined in this paper cluster around an early middle Miocene age (N10-N11). Wilson et al. (2017) noted that the Brasso Formation can be correlated with the upper N8 zone to N14 zones, and was deposited during two transgressive-regressive cycles, tectonically induced by the eastward paleo-advancement of the Caribbean Plate (see also Wilson 2007). The older cycle ended during the early part of Zone N10, the second, tectonically-induced transgression occurring during N10 and being followed by a regression that extended from late N10–N14, culminating with the Los Atajos Conglomerate Member of the Brasso Formation (Wilson et al. 2017). The work reviewed by Wilson et al. (2017) did not, however, cover the entire Brasso Formation, which Kugler (2001) suggested ranges upwards from the *Globigerinatella insueta* Zone (N7) and might locally extend as far back as the *Cata-*
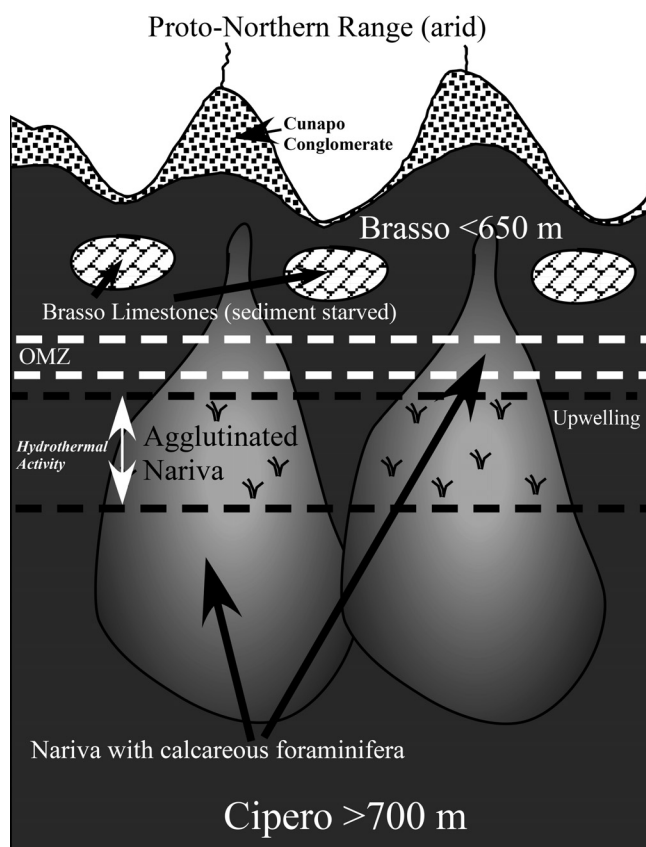

TEXT-FIGURE 6
Selected measures in the sampled exposures 1a, 2 and 3 at Raphael Street. A. Rarefied species richness S_r for N = 60 specimens, samples yielding >60 specimens only. B. Between-sample assemblage turnover index ATI_s for all samples from Exposures 1a, 2 and 3.

psydrax dissimilis Zone (N5). It is not yet known, therefore, if there were any transgressive-regressive cycles earlier than those reviewed by Wilson et al. (2017). Most of the Nariva Formation encountered in this study was deposited during the second of the tectonic pulses noted by Wilson et al. (2017). However, the occurrence of Oligocene Nariva Formation at Ben Lomond Quarry implies that there were older episodes of Nariva deposition. Higgs (2000) suggested that the southward decrease of grain size in the Nariva found nowadays indicates a provenance towards the north, although, given the Neogene rotation of the Central Range (Rohr 1990), the source probably lay more to the NW. It is thus possible that the commencement of Nariva deposition marks the subaerial exposure and erosion of the Proto-Caribbean Forebulge or Proto-Caribbean Ridge modelled by Pindell and Kennan (2007, figure 19) rather than the erosion of the accretionary prism as proposed by the same authors (Pindell and Kennan 2001).

At the most distal exposure at the Stripy Exposure near Philippine, the benthic foraminiferal assemblage of the Nariva beds is richly calcareous and of Cipero aspect. Wilson and Hayek (2015a) recorded abundant *Planulina wuellerstorfi* in the Upper Cipero Formation, and suggested this to indicate water depths >1000 m. This species was common at the Stripy Exposure, and so suggests a comparable paleodepth. Nevertheless, the limited occurrence of *Elphidium* sp. in the Nariva lithology at this site

TEXT-FIGURE 7
A generalized paleoenvironmental model for the Nariva Formation during early Middle Miocene times.

suggests that there was some downslope transport of foraminifera, this genus typically living in the photic zone (Murray 2006). The Cipero-aspect Nariva assemblage at this exposure indicates that the Nariva Formation is not at all sites characterised by agglutinated foraminifera. One of us (SS) is to undertake a more detailed analysis of the assemblage at this site as part of a study of Cipero benthic foraminifera.

The benthic Nariva association at all the other exposures is often sparse and consists almost entirely of agglutinated, organically-cemented foraminifera. That assemblage is here regarded as being of Brasso aspect, the specimens being identified mainly using the monograph by Renz (1948). It is unclear if this means that the species recorded here are also found in the Brasso Formation, or if Renz included some Nariva material in his work. The latter suggestions is thought to be the most likely, as Wilson (2004) listed few Nariva species in his study of Brasso foraminifera. The assemblage at Raphael Street consists largely of *Simobaculites saundersi* n. sp. and *Cribrostomoides carapitanus*, which together formed ~66% of the total recovery, with lesser *Trochammina* cf. *pacifica* (~10% of the total recovery). Species with labyrinthic wall structures at Raphael Street formed only 3% of the total recovery, attesting to the selective nature of Brönnimann's (1951, 1953) work on the Nariva assemblage. The sparser assemblage at the other exposures typically comprised many *Trochammina* spp. (especially *T.* cf. *pacifica*) and, at Tabaquite Heights, *Alveovalvulinella pozonensis*.

There is no obvious change in biofacies across the "Brasso aspect" sites, the assemblage at each being a variation of the agglutinated assemblage. Regarding the Point Radix Fault of Pindell and Kennan (2007), the uniformity of the "Brasso aspect" foraminiferal biofacies does not support suggestion that the Nariva Fold-Thrust Belt is bisected by a major transform fault of post-10 Ma age, which would be expected to juxtapose differing biofacies. It might be suggested that such a fault separates the "Brasso aspect" exposures from the "Cipero aspect" Stripy Exposure near Philippine. However, it might equally be suggested that the southward transition from the "Brasso aspect" biofacies to the "Cipero aspect" biofacies at the Stripy Exposure reflects the disposition of the Nariva Formation across the paleo-continental slope postulated by Higgs (2000) and simply reflects a transition from shallower-water deposits currently to the north, to deeper water to the present-day south. Some independent evidence supports the model proposed by Higgs (2000). A gravity survey presented by Francis et al. (2007, figure 6) did not show a fault extending from Point Radix across Trinidad. Nor is there any expression of such a fault on regional seismic surveys (Curtiss Archie, oral communication). Neither Hung (2005) nor Salazar et al. (2011, figure 1A) illustrated a transform fault as emanating from Point Radix, both noting it instead to lay at a deformation front. We conclude, then, that there was a simple deepening succession of benthic foraminiferal assemblages from central to southern Trinidad during Nariva times. However, as revealed by the sandwiching of the Oligocene Ben Lomond Quarry exposure between the Miocene exposures at the Stripy Exposure and Ben Lomond Playing Field, faulting and thrusting may have chopped up the Nariva Formation in post-Nariva times.

An explanation must be sought for the presence of the largely organically-cemented, agglutinated assemblage of the Nariva Formation between the richly calcareous assemblages of the neritic to middle bathyal Brasso Formation to the north and the lower bathyal to abyssal Cipero Formation to the south. Some evidence suggests that the Nariva paleoenvironment may either have been originally lacking in calcareous particles suitable for agglutination, or that such particles, such as planktonic foraminifera, were dissolved syndepositionally before the benthic foraminifera had had an opportunity to agglutinate them. Foraminifera that agglutinate calcareous particles in an area prone to dissolution develop large cavities in the surrounding insoluble test wall, whether it is organic or siliceous (Poag 2015). The genus *Simobaculites* Loeblich and Tappan is comparable to *Ammobaculites* Cushman. Cushman (1920) recorded *Ammobaculites agglutinans* between 49–4,333 m water depth and noted it to be "best developed in fairly deep, cold water". Kaminski and Khunt (1991) found two populations of *A. agglutinans* in the modern North Atlantic, separated by depth. Tellingly, these authors note that, while neritic to bathyal species may agglutinate calcareous fragments into their tests, abyssal specimens comprise quartz grains only within an organic cement. It is not known if *Simobaculites saundersi* n.sp. in the Nariva Formation would have agglutinated particles the same manner as *A. agglutinans*. However, all specimens of *Simobaculites saundersi* n.sp. had agglutinated particles that were insoluble in hydrochloric acid, and lacked cavities from which calcareous fragments had been dissolved. We therefore conclude that any calcareous particles at Raphael Street were dissolved before the foraminifera had a chance to agglutinate them.

Previous work has been equivocal regarding the Nariva paleoenvironment. Renz (1942) described it as being a piedmont facies. Such facies are typically associated with subaerial, arid environments (Smith 2000). It is possible that Renz was unaware of the foraminifera in the Nariva. He may, however, have noticed that pebbles in the Nariva Formation show evidence of desert varnish. Stainforth (1968) insisted on an inshore facies associated with a marine transgression for some of the Nariva grits and conglomerates. Kugler (2001) suggested that the Nariva assemblage resembles that of the western Venezuelan San Lorenzo Formation recorded by Blow (1959), but the latter formation has been ascribed to an outer neritic paleoenvironment on the basis of its shark assemblage (Sanchez-Villagra et al. 2010).

In view of the wide paleoenvironmental range proposed by previous workers, and in the spirit of the method of multiple working hypotheses suggested by Chamberlin (1897), five possible paleoenvironments that might have been inhabited by an agglutinated assemblage or prone to rapid calcite dissolution are examined here: (a) an association with high rates of fluvial run-off; (b) deposition within an intertidal zone; (c) deposition beneath the calcite compensation depth (CCD) – although this would contradict the southward-facing continental slope suggested by Higgs (2000) ; (c) an association with a virulent oxygen minimum zone (OMZ); and (d) deposition in association with hydrothermal activity.

Vergara et al. (1997) reported that the Chipaque Formation (Upper Cretaceous) of Colombia, South America, contains an almost entirely agglutinated assemblage dominated by *Haplophragmoides* spp. and *Ammobaculites* spp. They ascribed this to undersaturation of $CaCO_3$ over an inner to outer shelf, and in turn suggested this undersaturation to be due to high rates of fluvial runoff. While the Nariva Formation contains a similar assemblage, a similar paleoenvironment is highly improbable. Some clasts within the Nariva Formation and within the Guaracara Limestone Member of the Brasso Formation show desert varnish and a dreikanter-like morphology (Philip Farfan, unpublished work). This arid paleoenvironment reflects the influence of the changing position of the inter-tropical convergence zone, which currently lies over Trinidad for much of the year, but during Miocene times lay far to the north (Van Vliet-Lanoe 2007), inducing an arid Miocene paleoclimate in the Trinidad region that disallowed continual and high rates of fluvial runoff. Furthermore, the paleo-Orinoco River was during the deposition of the Nariva flowing into the Caribbean through western Venezuela and was not influencing the Trinidad region. Thus, the possibility that the Nariva was deposited in association with high rates of fluvial run-off is discounted.

Alve and Murray (1995) noted that only two modern environments are occupied by original dead assemblages (ODA) comprising only foraminifera with non-calcareous agglutinated tests: intertidal marshes or mangrove swamps, and seas below the CCD. Mangrove swamps, although at present widespread around Trinidad (Costelloe and Wilson 2017; Saunders 1957; Wilson et al. 2008), support foraminiferal communities with simple test morphologies and lack genera with complex interiors (e.g., *Cyclammina* spp., *Alveovalvulinella* spp.). Furthermore, they do not contain planktonic foraminiferal communities. We thus conclude that the Nariva Formation does not represent a mangrove swamp.

It might be suggested that the Nariva was instead deposited near or below the CCD, the sparse calcareous community perhaps being allochthonous and preserved due to rapid burial by turbidites. However, this is not accepted here. Murray and Alve (2000) found the diversity of agglutinated foraminifera, as measured using the Shannon Function H, to increase with water depth. Between samples BWPF-48 and BWPF-66 at Raphael Street, H for the almost entirely organically-cemented agglutinated assemblage ranged from 0.26–1.51, which Murray and Alve (2000) thought to be typical of shallow (0–200 m) water. Pflum and Frerichs (1976) recorded *Alveovalvulinella pozonensis* as being extant in the Gulf of Mexico at water depths as shallow as 232 m. Among the calcareous species, the rarely recovered *Chilostomella oolina* lives at bathyal depths (Holbourn et al. 2013), and *Globobulimina pacifica*, recorded at Tabaquite Heights, lives in water as shallow as middle bathyal (Rathburn et al. 2000). Although Rathburn et al. (2000) found *G. pacifica* to live off California in association with cold methane seeps, we dismiss such seeps as being a possible cause for the predominantly agglutinated Nariva assemblage, cold seeps being occupied by rich calcareous foraminiferal assemblages (Panieri et al. 2012; Sen Gupta et al. 2009) We thus conclude that the Nariva Formation was deposited at middle to lower bathyal depths. We must, however, seek some explanation other than deposition below the CCD for the almost entirely agglutinated assemblage.

It might be suggested that the Nariva Formation was deposited in the vicinity of a virulent OMZ, the frequent dominance of *Haplophragmoides* and *Trochammina*, which have been interpreted as indicators of low-oxygen environments with a high organic flux (Khunt and Kaminski 1990; Green et al. 2004; Katz et al. 2018), indicating suboxic waters. The source of the organic flux that induced the suboxia could not have been the nearby terrestrial hinterland, which was arid. Instead, we suggest the upwelling of nutrient enriched water may possibly be the cause. This had been widely invoked to explain features of both the benthic and planktonic foraminiferal assemblages in the overlying Brasso Formation (Wilson 2004, 2005, 2007, 2008a; Wilson et al. 2014).

Some evidence supports this OMZ hypothesis. Wilson et al. (2014) calculated the ATI_s for the entire (calcareous plus agglutinated) foraminifera in an OMZ with abundant *Bolivina subaenariensis* within the Brasso Formation. They found that values of ATI_s within the OMZ (mean = 0.74) were low compared to those between samples taken both above and below the OMZ, which they suggested to have lain at upper bathyal depths. Here we calculated the ATI_s for samples of the predominantly agglutinated assemblage of the Nariva Formation at Raphael Street and, for comparison, within the Lower Cruse Member. The mean values of ATI_s for the Raphael Street sites (0.387–0.659 per exposure) were even lower than those for the Brasso OMZ. These low mean values might in part reflect the low S of the agglutinated Nariva assemblage compared to that of the predominantly calcareous Brasso assemblage, but suggests also that dissolved oxygen may have been a major factor influencing the Nariva assemblage composition. The mean value of ATI_s for the Lower Cruse Member (0.87) was, however, higher than that for the Brasso Formation OMZ, suggesting that the Lower Cruse and the Nariva were deposited in distinctly differing paleoenvironments. The second line of evidence comes from comparison with known suboxic sites. Kaminski et al. (1995) examined agglutinated foraminifera in suboxic basins

TABLE 1
Latitude and longitude of sampled sites, indicating sample numbers used as each.

Localities (from south to north)	North	West	Samples
Philippine (Stripy Exposure)	10° 13.369' N	61° 27.260'W	BWPFSSSA-20 – 33
Tarouba Community Centre, Tarodale Hills	10° 17.042' N	61° 26.057'W	SSBA-1 – 2
Ben Lomond Quarry	10° 18.104' N	61° 23.885'W	BWPFCHSSKA-9 –14
Ben Lomond playing field	10° 18.708' N	61° 23.922'W	PFCHBW-1 – 4
Supermarket Quarry	10° 19.603' N	61° 22.612'W	PFCHBW-5 – 7
New Hillside, Bon Accord Development	10° 19.767' N	61° 22.202'W	PFCHBW-9
Old ladies' place	10° 20.085' N	61° 21.796'W	PFCHBW-8
Raphael Street	10° 20.362' N	61° 21.478'W	BWPF-48 – 66
Tabaquite Heights	10° 22.913' N	61° 19.251'W	BWPFSSSA-4 – 9

off California at depths between 26–1309 m (inner neritic to middle bathyal). Within the 26–874 m San Pedro Basin, they found that low diversity (3 to 11 species) assemblages and variable dominance reaching 95%. The Nariva Formation likewise has low S and high dominance. Virtually no calcite was recovered from the Nariva Formation. Kaminski et al. (1995) similarly found that calcium carbonate concentrations in the three suboxic basins they studied off California were low, with contents < 5% on the basin floors.

We believe, however, that dissolution of calcareous specimens due to the development of suboxic, acidic water in an OMZ is an unlikely explanation for the widespread development of the agglutinated Nariva assemblage. The OMZ developed during deposition of the Brasso Formation, which has been encountered in rocks of late N8–earliest N9 (Wilson 2004) and earliest N12 (Wilson 2008) age, and was thus approximately coeval with much of the Nariva Formation examined here, was situated at outer neritic to upper bathyal depths and underlain by oxygenated water. The invoked middle to lower bathyal paleodepths for the Nariva Formation would require the development of multiple OMZs separated by layers of oxygenated water. It is challenging to imagine such a situation.

Finally, it is possible that the widespread development of the agglutinated assemblage in the Nariva Formation was associated with hydrothermal activity (text-figures 3, 7). Jonasson et al. (1995) reported the distribution at benthic foraminifera at a 250 m by 700 m hydrothermal venting site at Middle Valley, Juan de Fuca Ridge, northeast Pacific (water depth 2430 m), Near active vents, temperatures were up to 274 °C. They found the sea floor beyond hydrothermal mounds to support a dominantly by calcareous assemblage, including numerous allochthonous species derived from the shelf via turbidity currents. In contrast, agglutinated foraminifera were dominant near the hydrothermal vents, although they did not occupy areas where temperatures were >20 °C. Species of the Family Hormosinidae, Subfamily Reophacinae, were especially common. Benthic foraminifera were rare at sites with active hydrogen sulphide venting, the sparse occurrence of calcareous benthic foraminifera in the vent areas being caused by enhanced carbonate dissolution at pH values of ≤5.2. Di Bella et al. (2016) examined the foraminiferal fauna around outer neritic hydrothermal springs in the Tyrrhenian Sea, central Mediterranean Basin. Comparing the assemblage adjacent to the vents with those beyond it, they found "a very peculiar living foraminiferal assemblage" of agglutinated species (*Spiculosiphon oceana*, *Jaculella acuta*, *Deuterammina rotaliformis*) under the direct influence of the vent, but noted that these are rare to absent elsewhere in the Mediterranean Sea. No carbon-

ate elements (including planktonic foraminifera) were recovered around the vents. The benthic foraminiferal fauna found was of low diversity with predominantly siliceous-cemented agglutinated species. They concluded that vent activity is likely, therefore, to be the main environmental driver on the composition of benthic foraminiferal distributions in the area.

The Nariva foraminiferal assemblage shows many similarities to the hydrothermal vent associations reported by Jonasson et al. (1995) and Di Bella et al. (2016), the agglutinated assemblage being of low diversity and acid insoluble. The areas in the Nariva Formation stained with hematite and manganese might indicate the precise locations of the hot springs, syndepositional tectonic activity perhaps being the cause of the hydrothermal activity. However, the Nariva assemblage was dominated by *Cribrostomoides* and *Trochammina* spp., rather than the Reophacidae. This assemblage indicates that the Nariva Formation was deposited under a high organic flux not found in the Tyrrhenian Sea. Given the middle to lower bathyal paleodepth invoked for the Nariva formation, planktonic foraminifera would be expected to be abundant. We concur with Guppy (1900) that calcareous foraminifera (including planktonic specimens) were dissolved and re-precipitated as gypsum, rather than excluded by turbid water as suggested by Higgs (2000). The acids responsible for the dissolution might have been vented from the hydrothermal springs, or perhaps associated with the interaction of hydrothermal activity and organic-rich sediment. Siesser and Rogers (1976) similarly recovered gypsum crystals from the South African continental slope that they thought had grown in organic-rich, suboxic sediment. They ascribed this precipitation to low pore-water pH, in turn a product of high rates of iron sulphide precipitation, which dissolved the calcareous foraminifera, the calcium ions reacting with sulphate ions in the pore water to form gypsum. Schnitker et al. (1980) showed in laboratory experiments on modern marine sediments that dissolution of calcareous foraminifera (especially *Elphidium ustilatum* and *E. subarcticum*) produces authigenic gypsum.

The benthic foraminiferal community structures in the Nariva Formation and the Lower Cruse Member of Trinidad differ markedly, despite both comprising predominantly agglutinated foraminifera. Both assemblages are indicative of bathyal or greater depths. However, both the Nariva and the Lower Cruse present values of the information function H far lower than would be predicted from the dissolution experiments of Murray and Alve (2000) for such depths. Wilson and Vincent (2014) did not disprove the suggestion by Jones (1998) that the paucity of calcareous foraminifera in the Lower Cruse may have arisen from the action of humic acids in the organic-rich sediment, which was deposited off the paleo-Orinoco River. No such river was present during the deposition of the Nariva Formation. The mean ATI_s for the two formations differing markedly and revealing more rapid rates of assemblage turnover during Lower Cruse times, we conclude that the predominantly agglutinated assemblages in the two lithostratigraphic units were the result of markedly different processes in differing paleoenvironments. Care must be taken, then, when using both the Nariva and Lower Cruse assemblages as analogues when interpreting predominantly agglutinated assemblages elsewhere, such as when Govindan (2004) suggested that the assemblages in the Ravva Formation of India resembled those of both the Nariva and the Lower Cruse.

SYSTEMATICS

In the following section the suprageneric classification of Kaminski (2014) is used. Assemblage slides from the Raphael Street localities were deposited in the collections of the European Micropalaeontological Reference Centre in Kraków, Poland.

Suborder ASTRORHIZINA Lankester 1885
Superfamily ASTRORHIZOIDEA Brady 1881
Family RHABDAMMINIDAE Brady 1884
Subfamily BATHYSIPHONINAE Avnimelech 1952
Nothia Pflaumann 1964

***Nothia* spp.**
Plate 1, figures 2a,b

Remarks: We included all thick-walled tubular fragments in this category. Some specimens have a finely agglutinated wall and resemble *Nothia robusta* (Grzybowski), while others have a more coarsely agglutinated wall.

Occurrence: Common in Samples BWPF-52 and -57.
Suborder KOMOKIOIDEA Tendal and Hessler 1977
Family RHIZAMMINIDAE Wieser 1931
Rhizammina Brady 1879

***Rhizammina* spp.**
Plate 1, figures 1a,b

Thin-walled, compressed specimens that are typically deformed.

Occurrence: Rare in the studied material. A typical specimen was found in Sample BWPF-49.

Suborder SACCAMMININA Lankester 1885
Superfamily SACCAMMINACEA Brady 1884
Family SACCAMMINIDAE Brady 1884
Subfamily SACCAMMININAE Brady 1884
Saccammina Carpenter 1869

Saccammina grzybowskii (Schubert 1902)
Plate 1, figures 3a,b

Reophax difflugiformis Brady. –GRZYBOWSKI 1898, p. 277, pl. 10, figs 11-12.
Reophax grzybowskii SCHUBERT 1902, p. 20, pl. 1, fig. 13.
Saccammina grzybowskii (Schubert). –KAMINSKI and GEROCH 1993, p. 248, pl. 2, figs 1a-4b.

Small subcircular test, a single finely agglutinated chamber.

Occurrence: Rare.

Suborder AMMODISCINA Mikhalevich 1980
Superfamily AMMODISCOIDEA Reuss 1862
Family AMMODISCIDAE Reuss 1862
Subfamily AMMODISCINAE Reuss 1962
Ammodiscoides Cushman 1909

***Ammodiscoides* sp.**
A small cone-shaped ammodiscid with a thin second chamber, about 8 volutions.

Occurrence: Rare in several samples. Similar forms have also been observed in the Agua Salada Formation of Venezuela (MAK personal observations).

Ammodiscus Reuss 1962

***Ammodiscus* sp.**
Plate 1, figures 4a-5b

A small, thin species with about 5–7 whorls and a depressed coil suture. Both microspheric and megalosphaeric forms are present. In microspheric forms, the second chamber does not increase in diameter with ontogeny, and because of this feature it resembles *Ammodiscus tenuissimus* Grzybowski. Megalosphaeric forms have a comparatively large and protruding globular proloculus. In these forms the test is thickest across the proloculus.

Occurrence: Single specimens in Samples BWPF-48, -49, -50, -51, and -53a.

Ammodiscus peruvianus Berry 1828
Ammodiscus peruvianus BERRY 1928, p. 392, fig. 28.

A small, oval species.

Remarks: Our specimens are similar to the type specimens from Peru preserved in the Sedgwick Museum in Cambridge (see Kaminski and Gradstein, 2005, pl. 18, figs. 1-2).

Suborder LITUOLINA Lankester 1885
Superfamily LITUOLOIDEA de Blainville 1827
Family HAPLOPHRAGMOIDIDAE Maync 1952
Haplophragmoides Cushman 1910

Haplophragmoides carinatus Cushman and Renz 1941
Plate 1, figure 8a,b

Haplophragmoides carinatus CUSHMAN and RENZ, 1941, pl. 1, fig. 1. –DIAZ DE GAMERO, 1977, pl. 3, fig. 1. –CICHA *et al*., 1998, p. 106, pl. 3, figs 1-2.–GREEN et al. 2004, p. 124, pl. 1, fig. 8.
Haplophragmoides carinatum (Cushman and Renz). –CUSHMAN and STAINFORTH, 1945, pl. 1, fig. 18. –BERMÚDEZ, 1949, p. 49, pl. 1, figs 43, 44.

Test small planispirally coiled with eight chambers in the last whorl, subcircular outline with acute periphery, possessing a narrow keel. Sutures flush with test, slightly darker coloration, radial, umbilical region depressed. Aperture a slit at base of last chamber, extends over entire width, test finely agglutinated with a smooth surface, often deformed.

Remarks: Cushman and Renz (1941) originally described this species from the lower to middle Miocene of the Agua Salada Group. Diaz de Gamero (1977) subsequently reported it from the upper Oligocene of the Falcon district of Venezuela.

Specimens in the Cushman Collection are from the upper Oligocene St. Croix beds of Trinidad and from the lower Oligocene Cipero Marl. As reported by Green et al. (2004), reports of the species should be taken with caution, because Cushman did not separate *H. carinatus* from the stratigraphically older species *Haplophragmoides walteri* (Grzybowski 1898). *Haplophagmoides carinatus* differs from *H. walteri* in its more lenticular cross-section.

Occurrence: Single specimen in Sample BWPF-51.

Family DISCAMMINIDAE Mikhalevich 1980
Discammina Lacroix 1932

Discammina compressa (Goës 1882)
Lituolina irregularis var. *compressa* GOËS 1882, p. 141, pl. 12, figs 421-423.
Discammina compressa (Goës).–LOEBLICH and TAPPAN, 1964, p. 226, pl. 136, fig. 10. – KAMINSKI et al. 1995, pl. 1, fig. 7.

Test free, strongly compressed, with an open umbilicus, about 6–7 chambers in the final whorl, coarsely agglutinated.

Occurrence: Several specimens in Sample BWPF-48.

Glaphyrammina Loeblich and Tappan 1984

Glaphyrammina americana (Cushman, 1910)
Plate 1, figures 9a,b

Ammobaculites americanus CUSHMAN 1910, p. 117, figs 184–185.– HERON-ALLEN and EARLAND 1932, p. 341, pl. 8, figs 15–17.
Glaphyrammina americana (Cushman).– JONES 1994, p. 40, pl. 34, figs 1–4.

Test free, broad and flattened, early portion planispirally enrolled and partially to completely evolute, with 9–10 chambers in the final whorl. Sutures curve back at the periphery, later portion may show a tendency to uncoil tangentially. Rare specimens have one or two chambers in the uncoiled part. Wall thin, coarsely agglutinated, with a rough surface, a mosaic of coarse quartz grains surrounded by dark cement.

Occurrence: Moderate abundance in the Rafael Street exposure.

Family LITUOLIDAE de Blainville 1827
Subfamily AMMOMARGINULININAE Podobina 1978
Ammobaculites Cushman 191

Ammobaculites agglutinans d'Orbigny 1846
Plate x, figures 7a,b

Ammobaculites agglutinans D'ORBIGNY 1846, p. 137, pl. 7, figs 10–12. –PAPP and SCHMIDT 1985, p. 54, pl. 45, figs. 6–9.

Remarks: Our specimens have only one or two uniserial chambers.

Occurrence: Single specimens.

Ammobaculites sp. 1
Test small, slender, consisting of a small coiled portion consisting of few chambers followed by a uniserial portion containing up to 5 chambers. Chambers in the uniserial part are inflated. Sutures depressed, wall medium to coarsely agglutinated. Aperture indistinct, without a neck.

Occurrence: Several good specimens in Sample BWPF-49.

Simobaculites Loeblich and Tappan 1984

Simobaculites saundersi Wilson and Kaminski, **n. sp.**
Plate 1, figures 6a,b; text-fig. 8

Derivation of name: The species is named in honor of John B. Saunders, in recognition of his contributions to the micropaleontology of Trinidad.

Description: Test medium size, laterally compressed, partially evolute with a deep umbilicus, 7–8 chambers in the planispiral part, sutures radial, appearing as dark bands. Wall coarsely agglutinated, consisting entirely of quartz. The aperture is usually

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PLATE 1
All specimens from the Raphael Street exposures. Scale bars = 100 µm

1a,b *Rhizammina* sp., sample BWPF-49

2a,b *Nothia* sp., sample BWPF-52

3a,b *Saccammina grzybowskii*, sample BWPF-50

4a–5b *Ammodiscus* sp., sample BWPF-57

6a,b *Simobaculites saundersi*, n. sp., holotype, Sample BWPF-57.
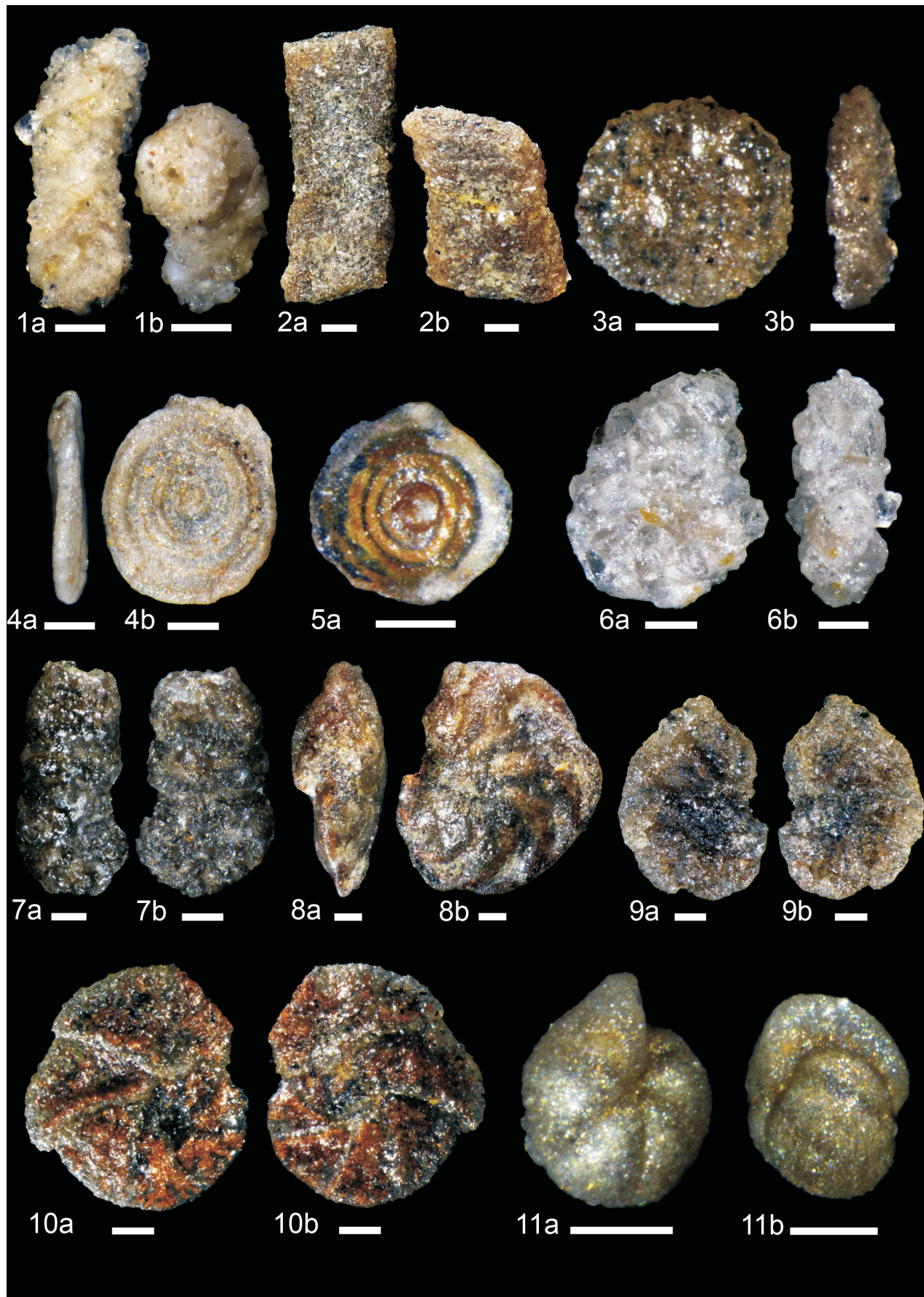
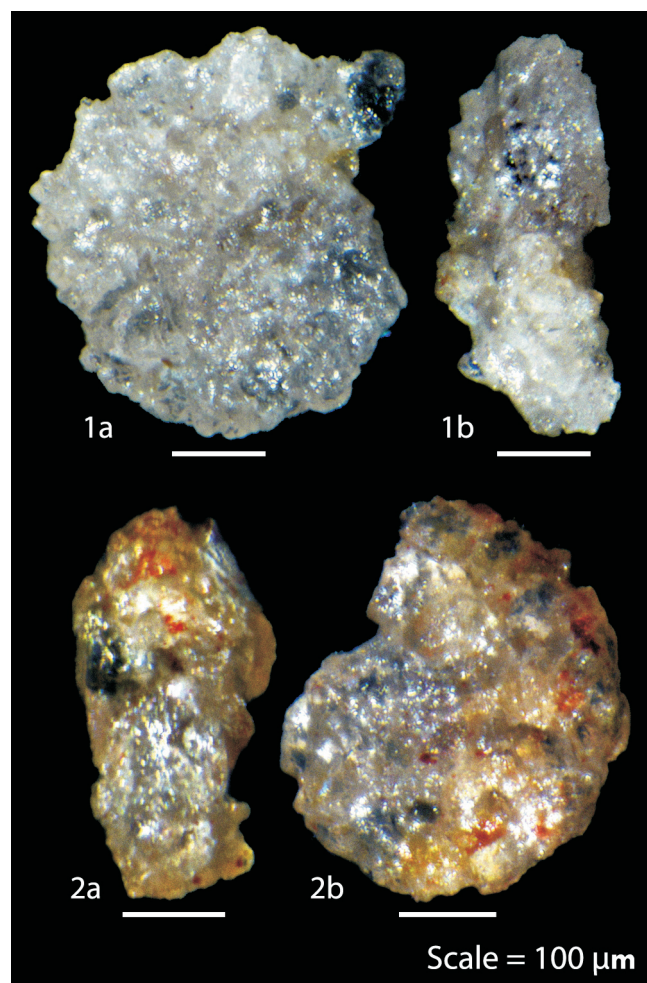7a,b *Ammobaculites agglutinans*, sample BWPF-50

8a,b *Haplophragmoides carinatus*, sample BWPF-51

9a,b *Glaphyrammina americana*, sample BWPF-50

10a,b *Discammina compressa*, sample BWPF-48

11a,b *Cribrostomoides carapitanus*, sample BWPF-50.

TEXT-FIGURE 8
Simobaculites saundersi, n.sp., paratypes, Sample BWPF-57.

indistinct, but in the coiled portion it appears to be areal, situated within a depression formed by flat agglutinated grains that surround it. Rare specimens display an uncoiled part consisting of one or two chambers, with symmetrically arched sutures.

Remarks: Simobaculites differs from *Ammobaculites* in its compressed test, evolute early coil, and in the later uniserial chambers being broad and flattened rather than rounded in cross section. It differs from *Ammomarginulina* in the symmetrical development of the rectilinear chambers, horizontal or symmetrically arched sutures, and aperture at the midpoint of the terminal surface, whereas *Ammomarginulina* has oblique sutures in the uniserial stage that are highest dorsally, and the aperture lies at the dorsal angle of the test.

The *Simobaculites saundersi* n.sp recovered in our samples were of two types. Rare specimens from Exposure 1b (BWPF-48 to BWPF-53) were coloured dark grey and are comprised of medium sized sand grains. The specimens from Exposures 2 and 3 were uncoloured and had agglutinated coarser sand grains than those from Exposure 1a

Occurrence: Well-preserved specimens are found in Samples BWPF-49, -53a and -57. A nearly monospecific assemblage is found in Sample BWPF-53a.

Type Specimens: Holotype (pl. 1, fig. 6) and paratypes (text-fig. 8) are deposited in the collections of the European Micropalaeontological Reference Centre, Kraków, Poland in Cabinet 7.

Superfamily RECURVOIDOIDEA Alekseychik-Mitskevich 1973
Family AMMOSPHAEROIDINIDAE Cushman 1927
Subfamily AMMOSPHAEROIDININAE Cushman 1927
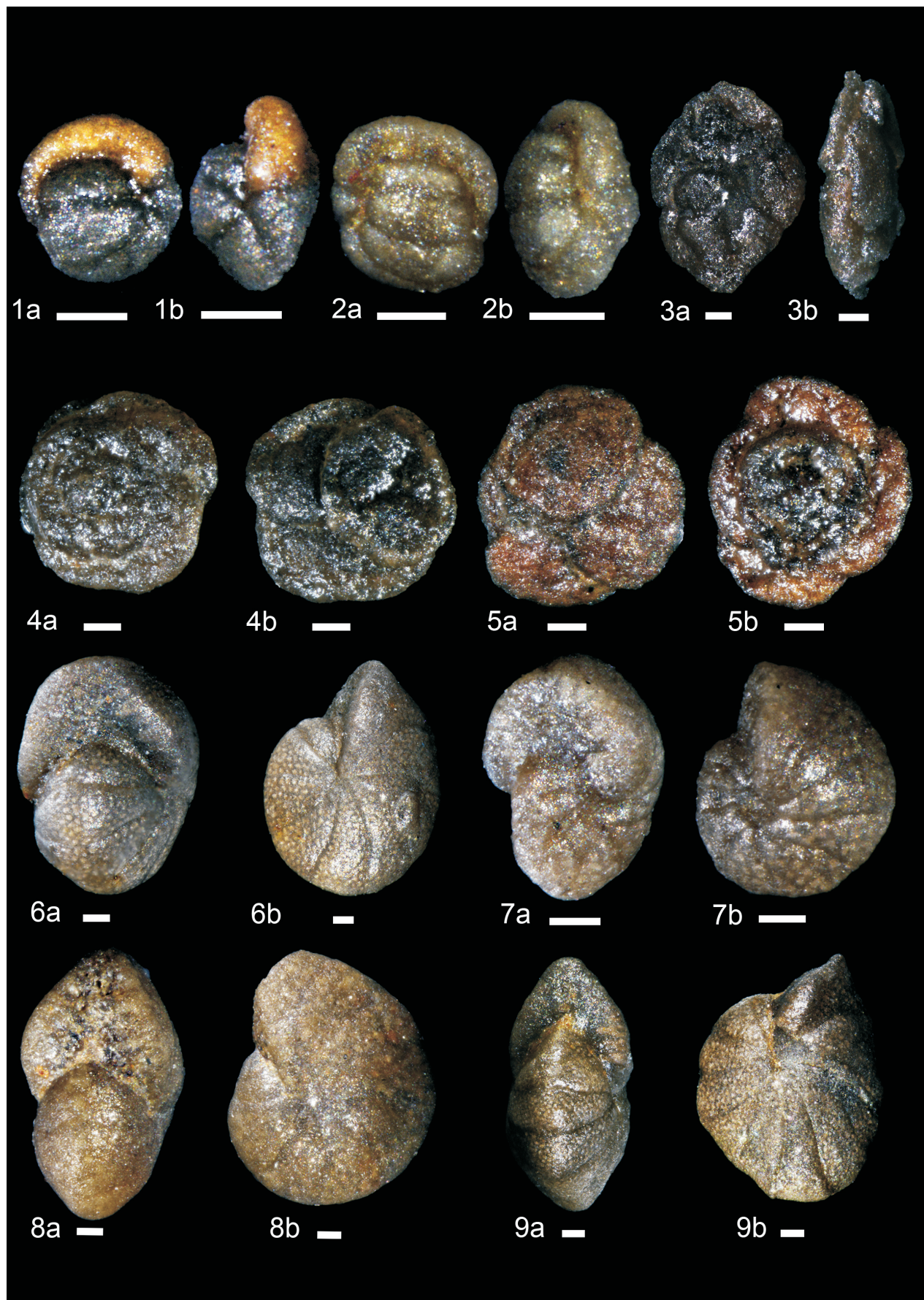*Ammosphaeroidina* Cushman 1910

Ammosphaeroidina pseudopauciloculata (Mjatliuk 1966)
Cystamminella pseudopauciloculata MJATLIUK 1966, p. 264, pl. 1, figs 5-7; pl. 2, fig. 6; pl. 3, fig. 3.

PLATE 2
All specimens from the Raphael Street exposures. Scale bars = 100 µm

1a,b   *Cribrostomoides carapitanus*, sample BWPF-50

2a,b   *Cribrostomoides carapitanus*, sample BWPF-52

3a,b   *Haplophragmoides* sp., sample BWPF-51

4a-5b   *Trochammina* cf. *pacifica*, sample BWPF-51

6a,b   *Cyclammina placenta*, sample BWPF-48, adult specimen

7a,b   *Cyclammina placenta*, sample BWPF-48, juvenile

8a,b   *Cyclammina placenta*, sample BWPF-44, adult specimen

9a,b   *Reticulophragmium acutidorsatum*, sample BWPF-48.

Ammosphaeroidina pseudopauciloculata (Mjatliuk 1966). – KAM-INSKI *et al.* 1988, p. 193, pl. 8, figs 3-5.

Medium sized streptospirally coiled test, subcircular lobate outline with only three chambers visible from the exterior, test wall smoothly finished. Aperture not visible. Specimens are always compressed.

Occurrence: The species is very abundant in the Paleocene Lizard Springs Formation of Trinidad (Kaminski et al. 1988). This is a rare species in the Nariva Formation, occurring as single specimens in Samples BWPF-53a and -57.

Family AMMOSPHAEROIDINIDAE Cushman 1927
Subfamily RECURVOIDINAE Alekseychik-Mitskevich 1973
Cribrostomoides Cushman 1910

Cribrostomoides carapitanus Kaminski, Crespo de Cabrera and Gonzalez 2011
Plate 1, figures 11a,b; Plate 2, figures 1a-2b

Cribrostomoides carapitanus KAMINSKI, CRESPO DE CABRERA and GONZALEZ 2011, p. 108, pl. 1, figs 1-5.
? *Haplophragmoides narivaensis* BRÖNNIMANN 1953, p. 96, pl. 15, fig. 4, text-figs 3a, 5 j-p.

Test free, small for the genus, thick, with a broadly rounded periphery, circular in outline. Chambers few in number, coiled planispirally in two whorls, with about five chambers in the last whorl. Sutures slightly depressed, radial, straight, appearing as thick lines on the surface of the test. Umbilicus is depressed, narrow, involute. Wall thin, finely agglutinated, with a very smooth surface. Aperture multiple, consisting of about 5–6 small round openings at the base of the last chamber, without lips.

Remarks: The species is characterized by its small size, thin wall that is susceptible to deformation. In most deformed specimens the aperture is not visible, but occasionally some black authigenic mineral substance (?pyrite) is present, and highlights

the small interiomarginal openings. It is possible that in his study of the Nariva assemblage Brönnimann recovered this species, describing it as *Haplophragmoides narivaensis*. Brönnimann reported that *H. narivaensis* is common in the Nariva formation, and also mentioned that he had difficulty observing the aperture. We suspect that this species may be the senior synonym of the species described as *Cribrostomoides carapitanus* from the Carapita Formation of Venezuela by Kaminski et al (2011). However, any revision or synonymy depends on comparing the type specimens of the two species.

Occurrence: Moderate to high abundance in the Rafael Street exposure.

Suborder TROCHAMMININA Saidova 1981
Superfamily TROCHAMMINOIDEA Schwager 1877
Family TROCHAMMINIDAE Schwager 1877
Subfamily TROCHAMMININAE Schwager 1877
Trochammina Parker and Jones 1859

Trochammina cf. pacifica Cushman
Plate 2, figures 4a-5b

Trochammina cf. *pacifica* Cushman – RENZ 1948, pl. 3, figs 4–5.

Test large, high trochospiral, with inflated chambers and depressed sutures. The adult test is comprised of 4–5 whorls, initially with four chambers per whorl, later reducing to three. Chambers increase in size rapidly. Wall medium to coarse, with visible agglutinated grains. Aperture indistinct, likely interiomarginal and umbilical in position. Specimens are typically flattened and display all stages of deformation.
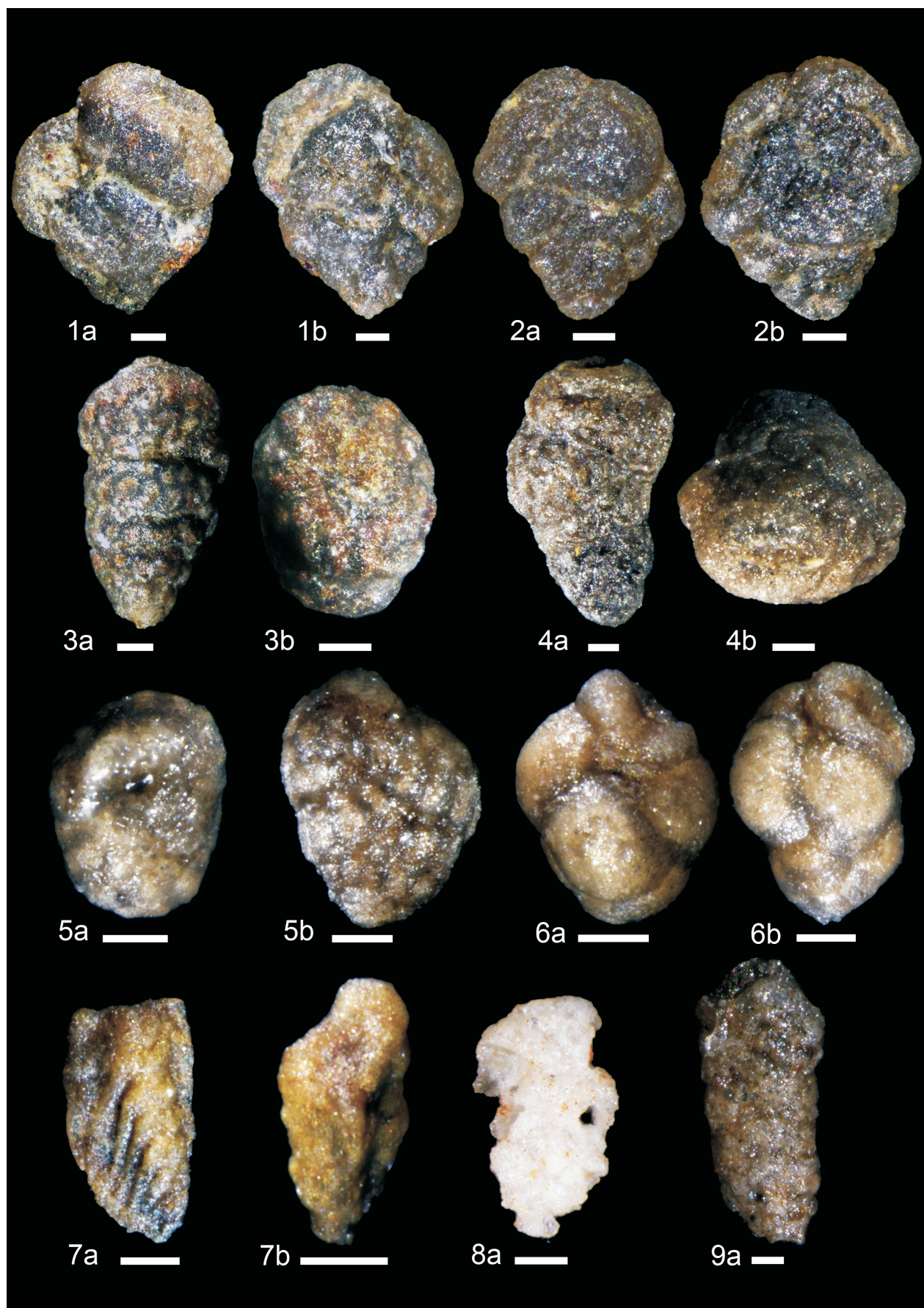
Remarks: The species is most similar to the illustration of "*Trochammina* cf. *pacifica*" of Renz (1948, pl. 3, figs 4–5). However, this form and our specimens from the Nariva Formation differ from *Trochammina pacifica* Cushman in their larger dimensions and in possessing a high trochospire with more rapidly enlarging chambers. Our specimens differ from

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PLATE 3
All specimens from the Raphael Street exposures. Scale bars = 100 µm

1a,b *Arenogaudryina flexilis*, sample BWPF-51

2a,b *Arenogaudryina flexilis*, sample BWPF-48

3a,b *Alveovalvulinella pozonensis*, sample BWPF-52

4a,b *Alveovalvulina suteri*, sample BWPF-48

5a,b *Jarvisella karamatensis*, sample BWPF-48

6a,b *Gravellina narivaensis*, sample BWPF-48

7a,b *Textularia* sp. 1, sample BWPF-48

8a,b *Textularia* sp. 2, sample BWPF-58

9a,b *Textularia* sp. 3, sample BWPF-65.

Trochammina altiformis (Cushman and Renz) described from the Lizard Springs Formation in possessing more rapidly enlarging chambers.

Occurrence: The species is common in the studied samples.

Trochammina sp. 2

Test small, resembling *Paragloborotalia opima* in shape, with four chambers in two whorls, quadrate in outline, with radial sutures. Spiral side is nearly flat, umbilical side is convex.

Occurrence: A rare species in Sample BWPF-53a.

Suborder VERNEUILININA Mikhalevich and Kaminski 2004
Superfamily VERNEUILINOIDEA Cushman, 1911
Family PROLIXOPLECTIDAE Loeblich and Tappan 1985
Genus *Arenogaudryina* Podobina 1975

Arenogaudryina flexilis (Cushman and Renz 1941)
Plate 3, figures 1a-2b

Valvulina flexilis CUSHMAN and RENZ, 1941, figs 16–17. –CUSHMAN and STAINFORTH 1945, p. 17, pl. 2, fig. 4. –CUSHMAN and RENZ 1948, p. 177, pl. 2, figs 12a-c. –RENZ 1948, pl. 2, figs 11–12. –BRÖNNIMANN 1953, textfig. 15. –DIAZ DE GAMERO 1977, pl. 3, fig. 13.

Text initially triserial, becoming biserial in the adult stage. Chambers are frequently severely deformed resulting in a wide range of morphologies. Only a few specimens closely resemble Cushman's original description.

Remarks: First described from the upper Oligocene "lower Agua Salada Formation" by Cushman and Renz (1941), the species is regarded to be the index taxon for the "Agua Salada Fauna" (Renz 1948; Katz et al. 2018). Its stratigraphic range in Trinidad was reported as upper Oligocene to middle Miocene by Brönnimann (1953). Blow (1959) recorded it from the Miocene upper Tocuyo and Pozon Formations of eastern Falcon, Venezuela. Diaz de Gamero (1977) established an uppermost Oligocene *V. flexilis* Zone in the Falcon Basin of Venezuela. It has also been observed in the lower Miocene of the Sirte Basin, Libya, offshore Cabinda, and in the Miocene of Transylvania (Preece 1999). It is commonly observed in the Miocene of the Gulf of Mexico offshore (Green et al. 2004; Katz et al. 2018).

We here transfer the species to the genus *Arenogaudryina* Podobina, 1975 (type species *Arenogaudryina granosa* Podobina, 1975). Because the wall of *A. flexilis* is thin and brown in color and specimens are always deformed; it contains no calcareous cement, as there is no reaction to acid. Moreover, its aperture is simple, without a valvulinid tooth. The genus *Arenogaudryina* is a Boreal form that was originally described from Campanian shallow-water deposits in western Siberia. The type species (paratype specimens are housed in the collections of the ECRC in Kraków) is more coarsely agglutinated than *"Valvulina" flexilis,* but in other aspects it has similar morphology. In our opinion *"Valvulina" flexilis* clearly fits within the definition of *Arenogaudryina*, thereby extending the known stratigraphic range of the genus into the Neogene.

Occurrence: Frequent in a few samples.

Suborder LOFTUSIINA Kaminski and Mikhalevich 2004
Superfamily LOFTUSIOIDEA Brady 1884
Family CYCLAMMINIDAE Marie 1941
Subfamily ALVEOLOPHRAGMIINAE Saidova 1981
Reticulophragmium Maync 1955

Reticulophragmium acutidorsatum (von Hantken 1868)
Plate 2, figure 9b

Haplophragmium acutidorsatum HANTKEN, von, 1868, p. 82, pl. 1, fig. 1a,b.
Reticulophragmium acutidorsatum (Hantken 1868).– KAMINSKI and GRADSTEIN, 2005, p. 488, text-fig. 122, pl. 122, figs 1-7.

A large specimen with >10 chambers in the final worl and an acute periphery.

Occurrence: A single specimen in Sample BWPF-48.

Subfamily CYCLAMMININAE Marie 1941
Cyclammina Brady 1879

Cyclammina placenta (Reuss 1851)
Plate 2, figures 6a-8b

Nonionina placenta REUSS 1851, p. 72, pl. 5, figs 33a,b.
Cyclammina placenta (Reuss 1851). – KAMINSKI and GRADSTEIN 2005, p. 480, pl. 119, figs 1-6.

Test involute planispiral flattened subcircular in outline with as many as 10 chambers in last whorl. Chambers increase in size gradually, sutures narrow, radial, straight in juveniles, becoming slightly curved in adults, but not sigmoidal, slightly depressed. Alveoles are equidimensional and distributed evenly over the entire inner surface of the test wall, and arranged in rows that parallel the sutures. There are approximately eight rows of alveoles in an adult chamber. Aperture is a low arch at base of last chamber with areal supplementary apertures in the center of the apertural face in larger specimens. Wall finely agglutinated with a smooth finish.

Remarks: Larger specimens have as many as eight supplementary areal apertures, each surrounded by a narrow raised lip. These most closely resemble the specimens from the Eocene of Labrador illustrated by Kaminski and Gradstein (2005, pl. 119, fig. 5). Juveniles have a more acute periphery in the early whorls, and do not have any visible supplementary apertures. These specimens more closely resemble *Reticulophragmium acutidorsatum* (von Hantken).

With its subacute periphery, *Cyclammina gasparensis* Bermúdez, 1949 described from the upper Oligocene of the Dominican Republic is similar in overall morphology, and was reported to possess a "cribrate aperture in the septal face of the last chamber". However, the drawings of Bermúdez do not clearly show supplementary apertures. Kender et al. (2008) illustrated a specimen without supplementary apertures as *Reticulophragmium gasparensis* from the offshore Congo Fan. In our opinion the Caribbean Oligocene assemblages from the Dominican Republic require further investigation and detailed comparison with *Cyclammina placenta*.

Occurrence: Single specimens in samples BWPF-42, -44, -48 and -50.

Suborder ATAXOPHRAGMIINA Fursenko 1958
Superfamily ATAXOPHRAGMIOIDEA Schwager 1877
Family GLOBOTEXTULARIIDAE Cushman 1927
Subfamily GLOBOTEXTULARIINAE Cushman 1927
Gravellina Brönnimann 1953

Gravellina narivaensis Brönnimann 1953
Plate 3, fig. 6a,b

Test subconical, high trochospiral coiling, constantly with four chambers per whorl that overlap strongly the earlier part of the test so that final whorl comprises nearly half the test length. Chamber interior simple. Wall agglutinated, thick, smoothly finished.

Occurrence: The species was originally described from the Nariva Formation (Brönnimann 1953). The species is also observed in the Falcon Basin in eastern Venezuela (MAK, personal observations). We found single specimens in Samples BWPF-48 and -49.

Subfamily LIEBUSELLINAE Saidova 1981
Jarvisella Brönnimann 1953

Jarvisella karamatensis Brönnimann 1953
Plate 3, figures 5a,b

Jarvisella karamatensis BRÖNNIMANN 1953, p. 88, pl. 15, figs 2, 3

Remarks: As pointed out by Brönnimann (1953), specimens can be confused with those of *A. suteri*. *Jarvisella* differs from *Alveovalvulina* by possessing vertical partitions instead of alveoles. Also, the specimens from the Nariva Formation are not as badly crushed as those of *A. suteri*, and have a narrower, less rapidly expanding test outline.

Occurrence: Frequent in Sample BWPF-48, rare in Sample -50.

Family TEXTULARIELLIDAE Grönhagen and Luterbacher 1966
Alveovalvulina Brönnimann 1951

Alveovalvulina suteri Brönnimann 1951
Plate 3, figures 4a,b

Alveovalvulina suteri BRÖNNIMANN 1951, p. 102, pl. 11, fig. 5. –GREEN et al. 2004, p. 128, pl. 5, figs 5, 6.

Test with early trochospiral stage of three or more chambers per whorl, later reduced to triserial, chambers strongly overlapping those of earlier whorls, wall agglutinated, with alveolar structure, aperture a low interiomarginal arch.

Occurrence: Single specimens occurring in several samples.

Alveovalvulinella Brönnimann 1953

Alveovalvulinella pozonensis (Cushman and Renz 1941)
Plate 3, figures 3a,b

Liebusella pozonensis CUSHMAN and RENZ 1941, p. 9, pl. 2, figs 1, 2. –RENZ 1948, p. 144, pl. 2, figs 21, 22.
Alveovalvulinella pozonensis (Cushman and Renz). –BRÖNNIMANN 1953, p. 91, pl. 15, fig. 3, text-figs 3e, 4a,b, 5a-d, 6g,h, 7. –GREEN et al. 2004, p. 128, pl. 6, figs 1, 2.

Remarks: Many of our specimens found appear to be juveniles with only one to three uniserial chambers. Thus species can be distinguished from *Alveovalvulina* by the presence of a uniserial part and presence of a lip.

Occurrence: Single specimens occurring in several samples.

Suborder TEXTULARIINA Delage and Hérouard 1896 emend. Kaminski, 2004
Superfamily TEXTULARIACEA Ehrenberg 1838
Family TEXTULARIIDAE Ehrenberg 1838
Subfamily TEXTULARIINAE Ehrenberg 1838
Genus *Textularia* Defrance 1824

***Textularia* sp. 1**
Plate 3, figures 7a,b

Specimen is wholly biserial, comprised of eight pairs of low chambers separated by raised sutures that are slightly arched. Periphery acute. The test has a raised and much thickened median line. Aperture indistinct.

Occurrence. A single specimen in Sample BWPF-48.

***Textularia* sp. 2**
Plate 3, figures 8a,b

A very coarsely agglutinated form made of quartz grains, chambers indistinct, poorly preserved.

Occurrence: A single specimen in Sample BWPF-58.

***"Textularia"* sp. 3**
Plate 3, figures 7a,b

Test biserial, comprised of up to seven pairs of chambers, oval in cross section, increasing in width very gradually as chambers are added. Wall is likely non-calcareous, with visible quartz grains and rare dark mineral grains.

Remarks: Owing to its non-calcareous wall, it is only tentatively placed in the genus *Textularia*.

Occurrence: Two specimens in Sample BWPF-65.

CONCLUSIONS

Hydrocarbon exploration offshore Trinidad is to move presently into deep water. A thorough knowledge of the region's geological evolution is vital if this exploration is to attain its full potential. The age and paleoenvironment of the Nariva Formation have long been missing pieces from the puzzle of Trinidad's early to middle Miocene evolution. Samples collected along a transect in central Trinidad indicate that the Nariva Formation was deposited at middle to lower bathyal depths on an eastward-facing paleo-slope during Oligocene to early middle Miocene times. This region of the seafloor lay between the carbonate prone areas of the Brasso shelf and the lower bathyal to abyssal Cipero Formation. Where the Nariva interfingers with the Cipero, the former yields a benthic foraminiferal assemblage typical of the latter, indicating that the Nariva Formation is not everywhere characterised by acid-insoluble agglutinated foraminifera. The uniformity of Nariva benthic foraminiferal biofacies elsewhere indicates that there has been little if any lateral displacement of Nariva exposures in post-Nariva times.

We conclude that the benthic foraminiferal recovery is elsewhere generally sparse with pockets of richer recovery, such as at Raphael Street and Tabaquite Heights, where the rocks are stained with hematite and manganese. The sparse recovery in

unstained rocks might reflect a high rate of sedimentation inducing a dilute assemblage. The richer recovery of *Trochammina* spp., *Cribrostomoides carapitanus* and *Simobaculites saundersi* n. sp. around the stained areas we conclude to reflect the influence of hydrothermal activity in an area of high organic productivity associated with upwelling.

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REFERENCES

ALGAR, S. T. and PINDELL, J. L., 1993. Structure and deformation history of the Northern Range of Trinidad and adjacent areas. *Tectonics,* 12: 814–829.

ALVE, E., and MURRAY, J. W., 1995. Experiments to determine the origin and palaeoenvironmental significance of agglutinated foraminiferal assemblages. In: Kaminski, M.A., Geroch, S. and Gasinski, M.A., Eds., *Proceedings of the Fourth International Workshop on Agglutinated Foraminifera.* Grzybowski Foundation Special Publication, 3: 1–11.

ASLAN, A., WHITE, W. A., WARNE, A. G., and GUEVARA, E. H., 2003. Holocene evolution of the western Orinoco Delta, Venezuela. *Geological Society of America Bulletin*, 115: 479–498.

BARKER, R. W., 1960. Taxonomic notes on the species figured by H.B. Brady in his report on the foraminifera dredged by H.M.S. *Challenger* during the years 1873-1876. *Society of Economical Paleontologists and Mineralogists*, 238 pp.

BATJES, D. A. J., 1968. Palaeoecology of foraminiferal assemblages in the late Miocene Cruse and Forest Formations of Trinidad, Antilles. *Proceedings of the Fourth Caribbean Geological Conference, 1965*, 141–156.

BERMÚDEZ, P. J., 1949. Tertiary smaller foraminifera of the Dominican Republic. *Contributions from the Cushman Laboratory for Foraminiferal Research, Special Publication,* 25, 322 pp.

BENDER, H., 1995. Test structure and classification in agglutinated foraminifera. In: Kaminski, M. A., Geroch, S. and Gasinski, M. A., Eds., *Proceedings of the Fourth International Workshop on Agglutinated Foraminifera.* Grzybowski Foundation Special Publication, 3: 27–70.

BERNHARD, J. M. and REIMERS, C. E., 1991. Benthic foraminiferal population fluctuations related to anoxia: Santa Barabara Basin. *Biogeochemistry,* 15: 127–149.

BERNHARD, J. M., VISSCHER, P. T. and BOWSER, S. S., 2003. Submillimeter life positions of bacteria, protists, and metazoans in laminated sediments of the Santa Barbara Basin. *Limnology and Oceanography,* 48: 813–828.

BERRY, E.W., 1928. The smaller foraminifera of the middle Lobitos shales of northwestern Peru. *Eclogae Geologae Helvetiae,* 21: 390–405.

BLANCHET, C. L., KASTEN, S., VIDAL, L., POULTON, S. W., GANESHRAM, R. and THOUVENY, N., 2012. Influence of diagenesis on the stable isotopic composition of biogenic carbonates from the Gulf of Tehuantepec oxygen minimum zone. *Geochemistry, Geophysics, Geosystems,* 13: 1–20.

BLOW, W. H. 1959. Age, correlation, and biostratigraphy of the Upper Tocuyo (San Lorenzo) and Pozón Formations, eastern Falcón, Venezuela. *Bulletins of American Paleontology,* 39 (178): 67–251.

BLOW, W. H., and BANNER, F. T., 1962. The Mid-Tertiary (Upper Eocene to Aquitanian) Globigerinaceae. In Eames, F. E., Ed., *Fundamentals of Mid-Tertiary stratigraphical correlation.* Cambridge University Press, UK, 61–151.

BOLLI, H. M., 1957. Planktonic Foraminifera from the Oligocene-Miocene Cipero and Lengua Formations of Trinidad, B.W.I. *Bulletin of the United States National Museum,* 215: 97–123.

BOLLI, H. M., BECKMANN, J.-P. and SAUNDERS, J. B., 1995. *Benthic foraminiferal biostratigraphy of the south Caribbean region.* Cambridge University Press, Cambridge, UK, 408 pp.

BORSTAD, G., 1982. The influence of the meandering Guiana Current on surface conditions near Barbados: Temporal Variations of Trichodesmium (Cyanophyta) and other plankton. *Journal of Marine Research,* 40: 435–452.

BOUDAGHER-FADEL, M. K., and PRICE, G. D., 2010. American Miogypsinidae: An analysis of their phylogeny and biostratigraphy. *Micropaleontology,* 56: 567–586.

BRÖNNIMANN, P., 1951. *Guppyella, Alveovalvulina* and *Discamminoides*, new genera of arenaceous foraminifera from the Miocene of Trinidad, B.W.I. *Contributions from the Cushman Foundation for Foraminiferal Research,* 2: 97–105.

———, 1953. Arenaceous foraminifera from the Oligo-Miocene of Trinidad. *Contributions from the Cushman Foundation for Foraminiferal Research,* 4: 87–100.

BUZAS, M. A. and HAYEK, L.C., 2011. Community structure: Global evaluation and the role of within community beta-diversity. *Journal of Foraminiferal Research,* 41: 138–154.

BUZAS, M. A., SMITH, R. K. and BEEM, K. A., 1977. Ecology and systematics of foraminifera in two *Thalassia* habitats, Jamaica, West Indies. *Smithsonian Contributions to Paleobiology,* 31: 1–139.

CARR-BROWN, B. and FRAMPTON, J., 1979. An outline of the stratigraphy of Trinidad. *4th Latin American Geological Congress, Volume Field Guide, Trinidad, Tobago, Barbados, July 1979: Port of Spain, Trinidad, Key Caribbean Publications*, 7–19.

CARTER, M. C., 1966. A note on the re-investigation of the foraminiferal localities of the Cipero Coast, Trinidad, West Indies. *Caribbean Journal of Science,* 6: 89–92.

CHAMBERLIN, T. C., 1897. The method of multiple working hypotheses. *Journal of Geology,* 5: 837–848.

CICHA, I., RÖGL, F., RUPP, C., and CTYROKA, J., Eds., 1998. Oligocene-Miocene foraminifera of the Central Paratethys. *Abhandlungen der Senckenbergischen Naturforschenden Gesellschaft,* 549: 1–325.

COMEAU, P. L., 1991. Geological events influencing natural vegetation in Trinidad. *Living World: Journal of the Trinidad and Tobago Field Naturalists' Club 1990–1991, 100th Anniversary Issue*, 29–38.

COSTELLOE, A. and WILSON, B., 2017. The effect of seasonal sea level changes on tropical intertidal foraminiferal assemblages of Trinidad (southeastern Caribbean Sea). In: Kaminski, M. A. and Alegret, L., Eds., *Proceedings of the Ninth International Workshop on Agglutinated Foraminifera.* Grzybowski Foundation Special Publication, 22: 39–49.

CUSHMAN, J. A., 1910. A monograph on the foraminifera of the North Pacific Ocean; Part I - Astrorhizidae and Lituolidae. *United States National Museum Bulletin,* 71, 134 pp.

———, 1918. The Foraminifera of the Atlantic Ocean. Part 1: Astrorhizidae. *United States National Museum Bulletin,* 104 (1): 1–111.

———, 1920. The Foraminifera of the Atlantic Ocean. Part 2: Lituolidae. *United States National Museum Bulletin,* 104 (2): 1–89.

———, 1922. The Foraminifera of the Atlantic Ocean. Part 3: Textulariidae. *United States National Museum Bulletin,* 104 (3): 1–149.

CUSHMAN, J. A. and RENZ, H. H., 1941. New Oligocene – Miocene foraminifera from Venezuela. *Contributions from the Cushman Laboratory for Foraminiferal Research*, 17: 1–27.

CUSHMAN, J. A. and STAINFORTH, R. M., 1945. The Foraminifera of the Cipero Marl Formation of Trinidad, British West Indies. *Cushman Laboratory for Foraminiferal Research, Special Publication,* 14: 1–75.

DI BELLA, L., INGRASSIA, M., FREZZA, V., CHIOCCI, F. L., and MARTORELLI, E., 2016. The response of benthic meiofauna to hydrothermal emissions in the Pontine Archipelago, Tyrrhenian Sea (central Mediterranean Basin). *Journal of Marine Systems,* 164: 53–66.

DÍAZ DE GAMERO, M. L., 1996. The changing course of the Orinoco River during the Neogene: a review. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 123: 385–402.

D'ORBIGNY, A., 1846. *Die fossilen Foraminiferen des tertiären Bekens von Wien.* Gide et Comp. Paris, 312 pp.

DUNCAN, P. M., 1868. On the fossil corals (Madreporaria) of the West Indian islands. *Quarterly Journal of the Geological Society,* 24: 9–33.

DUNCAN, C. P., and SCHLADOW, S. G., 1981. World surface currents from ship's drift observations. *International Hydrographic Review,* 58: 101–112.

ERLICH, R.N., FARFAN, P.F. and HALLOCK, P., 1993. Biostratigraphy, depositional environments, and diagensis of the Tamana Formation, Trinidad: a tectonic marker horizon. *Sedimentology,* 40: 743–768.

FIGUEIREDO, J. P., HOORN, C., VAN DER VEN, P., and SOARES, E., 2009. Late Miocene onset of the Amazon River and the Amazon deep-sea fan: Evidence from the Foz do Amazonas Basin. *Geology,* 37: 619–622.

FINGER, K. L., 2013. Miocene foraminifera from the south-central coast of Chile. *Micropaleontology,* 59: 341–492.

FRANCIS, A. K., JAGGERNAUTH, D., WILLIAMS, E. A., and SAHOO, M. R., 2007. Revised structural interpretation of the Southern Basin, Trinidad using gravity, magnetic, topographic and seismic data: Implications for hydrocarbon prospectivity of the basin. *The 4th Geological Conference of the Geological Society of Trinidad and Tobago, June 17-22, 2007, Hilton Trinidad and Conference Center Port-of-Spain, Trinidad and Tobago, "Caribbean Exploration – Planning for the Future"* 1: 1–25.

GOËS, A., 1882. On the reticularian Rhizopoda of the Caribbean Sea. *Kongl. Svenska Vetenskaps-Akademiens Handlingar*, 19: 1–151.

GOVINDAN, A., 2004. Miocene deep water agglutinated foraminifera from offshore Krishna-Godavari Basin, India. *Micropaleontology,* 50: 213–252.

GREEN, R. C., KAMINSKI, M. A. and SIKORA, P. J., 2004. Miocene deep water agglutinated foraminifera from Viosca Knoll, offshore Louisiana (Gulf of Mexico). In Bubík, M. and Kaminski, M. A. Eds., *Proceedings of the Sixth International Workshop on Agglutinated Foraminifera.* Grzybowski Foundation Special Publication, 8: 119–144.

GUPPY, R. J. L., 1900. On the Naparima rocks, Trinidad. *Geological Magazine*, 1900: 522–525.

GRZYBOWSKI, J., 1898. Otwornice pok³adów naftonosnych okolicy Krosna. Rozprawy Wydzia³u Matematyczno-Przyrodniczego, Akademia Umiejêtnoœci w Krakowie, serya 2, 33: 257–305.

HAMMER, Ø., HARPER, D. A. T. and RYAN, P. D., 2001. PAST: Paleontological Statistics Software Package for Education and Data Analysis. *Palaeontologia Electronica,* 4. http://palaeo-electronica.org/2001_2001/past/issue2001_2001.htm.

HANTKEN, M. von, 1868. A kis-czelli tályag foraminiferái. *Magyar Foldtani Társulat Munkálatai, Pest,* 4: 75–96.

HAYEK, L. C. and BUZAS, M. A. 1997. *Surveying Natural Populations.* New York: Columbia University Press, 563 pp.

———, 2010. *Surveying Natural Populations.* New York: Columbia University Press, 590 pp.

HAYEK, L. C. and WILSON, B., 2013. Quantifying Assemblage Turnover and Species Contributions at Ecologic Boundaries. *PLoS ONE,* 8 (10), p. e74999.

HERON-ALLEN, E. and EARLAND, A., 1932. Foraminifera. Part 1. The ice-free area of the Falkland Islands and adjacent seas. *Discovery Reports*, 4: 291–460 + 17 pls.

HIGGS, R., 2000. The Chaudiere and Nariva wildflysch of Central Trinidad: a modern sedimentological perspective. *Geological Society of Trinidad and Tobago 2000 Conference: The Hilton, Port of Spain, Trinidad, http://archives.datapages.com/data/gstt/*SS04.htm.

HOLBOURN, A., HENDERSON, A. S. and MACLEOD, N., 2013. *Atlas of Benthic Foraminifera.* John Wiley and Sons, Chichester, UK, 642 pp.

HU, C., MONTGOMERY , E. T., SCHMITT, R. W. and MULLER-KARGER, F. E., 2004. The dispersal of the Amazon and Orinoco River water in the tropical Atlantic and Caribbean Sea: Observation from space and S-PALACE floats. *Deep-Sea Research* II, 51: 1151–1171.

HUNG, E. J., 2005. Thrust belt interpretation of the Serranía del Interior and Maturín subbasin, eastern Venezuela. *Geological Society of America Special Paper,* 394: 251–270.

INGLE, J. C., 1980. Cenozoic paleobathymetry and depositional history of selected sequences within the southern California continental borderland. In: Sliter, W. V., Ed., *Studies in marine micropaleontology and paleoecology—A memorial volume to Orville L. Bandy.* Cushman Foundation for Foraminiferal Research Special Publication, 19: 163–195.

JOHNSON, K. G., SÁNCHEZ-VILLAGRA, M. R. and AGUILERA, O. A., 2009. The Oligocene–Miocene transition on coral reefs in the Falcón Basin (NW Venezuela). *Palaios,* 24: 59–69.

JONASSON, K. E., SCHROEDER-ADAMS, C. J., and PATTERSON, R. T., 1995. Benthic foraminiferal distribution at Middle Valley, Juan

de Fuca Ridge, a northeast Pacific hydrothermal venting site. *Marine Micropaleontology,* 25: 151–167.

JONES, R. W., 1994. *The Challenger Foraminifera.* Oxford University Press, 149+vi pp + 117 pl.

———, Palaeoenvironmental interpretation of the Late Miocene and Pliocene of Trinidad based on micropalaeontological data. In: Ali, W., Paul, A., and Young On, V., Eds., *Transactions of the 3rd geological conference of the Geological Society of Trinidad and Tobago and 14th Caribbean Geological Conference, Volume 1: Port-of-Spain, Trinidad*, 88–101.

———, 2009. Stratigraphy, palaeoenyironmental interpretation and up-lift history of Barbados based on foraminiferal and other palaeontological evidence. *Journal of Micropalaeontology,* 28: 37–44.

KAIHO, K., 1999. Evolution in the test size of deep-sea benthic foraminifera during the past 120 m.y. *Marine Micropaleontology,* 37: 53–65.

KAMINSKI, M. A., 2014. The year 2010 classification of the agglutinated foraminifera. *Micropaleontology*, 61: 89–108.

KAMINSKI, M. A. and GEROCH, S., 1993. A revision of foraminiferal species in the Grzybowski Collection. In: Kaminski, M.A., Geroch, S. and Kaminski, D., Eds., *The Origins of Applied Micropaleontology: The School of Jozef Grzybowski.* Grzybowski Foundation Special Publication no. 1. Alden Press, Oxford, 239–323.

KAMINSKI, M. A. and GRADSTEIN, F. M., 2005. *Atlas of Paleogene cosmopolitan deep-water agglutinated foraminifera.* Grzybowski Foundation Special Publication, 10, 547 pp.

KAMINSKI, M. A. and KUHNT, W., 1991. Depth related shape vatiation in *Ammobaculites agglutinans* (d'Orbigny). *Annales Societatis Geologorum Poloniae,* 61, 221–230.

KAMINSKI, M. A., BOERSMA, A., TYSZKA, J. and HOLBOURN, A. E. L. 1995. Response of deep-water agglutinated foraminifera to dysoxic conditions in the California Borderland basins. In: Kaminski, M.A., Geroch, S. and Gasinski, M.A., Eds., *Proceedings of the Fourth International Workshop on Agglutinated Foraminifera.* Grzybowski Foundation Special Publication, 3: 131–140.

KAMINSKI, M. A., CRESPO de CABRERA, S. and GONZALEZ, I. 2011. *Cribrostomoides carapitanus*, n.sp., a new foraminiferal species from the Miocene of eastern Venezuela. In: Kaminski, M.A. and Filipescu, S., Eds, *Proceedings of the Eighth International Workshop on Agglutinated Foraminifera.* Grzybowski Foundation Special Publication, 16: 107–110.

KAMINSKI, M. A., GRADSTEIN, F. M., BERGGREN, W. A., GEROCH, S. and BECKMANN, J. P. 1988. Flysch-type agglutinated foraminiferal assemblages from Trinidad: Taxonomy, Stratigraphy and Paleobathymetry. In: Gradstein, F.M. and Rögl, F., Eds., *Proceedings of the Second Workshop on Agglutinated Foraminifera, Vienna 1986. Abhandlungen der Geologishen Bundesanstalt,* 41: 155–228.

KATZ, M. E., MILLER, K. G., KAMINSKI, M. A. and BROWNING, J. V., 2018. Neogene benthic foraminiferal biofacies, paleobathymetry, and paleoenvironments of a Gulf of Mexico transect. *Journal of Foraminiferal Research*, 48: 356–372.

KENDER, S., KAMINSKI, M. A. and JONES, R. W., 2008. Oligocene deep-water agglutinated foraminifera from the Congo Fan, Offshore Angola: Palaeoenvironments and assemblage distributions. In: Kaminski, M.A. and Coccioni, R. Eds, *Proceedings of the Seventh*

International Workshop on Agglutinated Foraminifera. Grzybowski Foundation Special Publication, 13: 107–156.

KENNETT, J. P., and SRINIVASAN, M. S., 1983. *Neogene Planktonic Foraminifera: A Phylogenetic Atlas*. Stroudsburg, Pennsylvania, Hutchinson Ross Publishing Company, 262 pp.

KHUNT, W. and KAMINSKI, M. A., 1990. Paleoecology of late Cretaceous to Paleocene deep-water agglutinated foraminifera from the North Atlantic and Western Tethys. In: Hemleben, C. et al., Eds., *Palaeoecology, Biostratigraphy and Taxonomy of Agglutinated Foraminifera.* NATO-ASI Series C 327: 433–505.

KUGLER, H. G., 1996. *Treatise on the Geology of Trinidad: Detailed geological maps and sections*. Basel, Switzerland, Natural History Museum, Basel.

———, 2001. *Treatise on the Geology of Trinidad. Part 4: Paleocene to Holocene Formations*. Basel, Switzerland, Museum of Natural History, 309 pp.

LOEBLICH, A.F. and TAPPAN, H., 1964. Sarcodina chiefly "Thecamoebians" and Foraminiferida. In: Moore, R.C., Ed., *Treatise on invertebrate paleontology, part C, Protista.* University of Kansas Press. 900 pp.

MAGURRAN, A. E., 2004. *Measuring Biological Diversity.* Oxford, UK: Blackwell Publishing, 256 pp.

MANCIN, N., 2001. Agglutinated foraminifera from the epiligurian succession (Middle Eocene/Lower Miocene, northern Apennines, Italy): scanning electron microscopic characterization and paleoenvironmental implications. *Journal of Foraminiferal Research,* 31: 294–308.

MICHELSON, J. E., 1976. Miocene deltaic oil habitat, Trinidad. *American Association of Petroleum Geologists, Bulletin,* 60: 1502–1519.

MJATLIUK, E. V., 1966. K voprosu o foraminiferakh c kremnevnym skeletom [On the question of foraminifera with a siliceous skeleton]. *Voprosy Mikropaleontologii,* 10: 255–269.

MULLINS, H. T., THOMPSON, J. B., MCDOUGALL, K. and VERCOUTERE, T. L., 1985. Oxygen-minimum zone edge effects: Evidence from the central California coastal upwelling system. *Geology,* 13: 491–494.

MURRAY, J. W., 2003. An illustrated guide to the benthic foraminifera of the Hebridean Shelf, west of Scotland, with notes on their mode of life. *Palaeontologia Electronica,* 5: 1–31.

———, 2006. *Ecology and Applications of Benthic Foraminifera*. Cambridge, UK, Cambridge University Press, 438 pp.

MURRAY, J. W. and ALVE, E. 2000. Do calcareous dominated shelf foraminiferal assemblages leave worthwhile ecological information after their dissolution? In: Hart, M.B., Kaminski, M.A. and Smart, C.W. Eds., *Proceedings of the Fifth International Workshop on Agglutinated Foraminifera.* Grzybowski Foundation Special Publication, 7: 311–331.

NAIK, S. S., GODAD, S. P., NAIDU, P. D., TIWARI, M. and PAROPKARI, A. L., 2014. Early to late-Holocene contrast in productivity, OMZ intensity and calcite dissolution in the eastern Arabian Sea. *The Holocene,* 24: 749–755.

PANIERI, G., CAMERLENGHI, A., CACHO, I., CERVERA, C. S., CANALS, M., LAFUERZA, S., and HERRERA, G., 2012. Tracing seafloor methane emissions with benthic foraminifera: Results from the Ana submarine landslide (Eivissa Channel, Western Mediterranean Sea). *Marine Geology,* 291-294: 97–122.

PAPP, A. and SCHMID, M. E., 1985. The fossil Foraminifera of the Tertiary Basin of Vienna: Revision of the monograph by Alcide d'Orbigny (1846). *Abhandlungen der geologischen Bundesanstalt,* 37, 1–311.

PFLUM, C. E., and FRERICHS, W. E., 1976. Gulf of Mexico deep-water foraminifers. *Cushman Foundation for Foraminiferal Research, Special Publication,* 14: 1–125.

PINDELL, J. L., and KENNAN, L., 2001. Processes and events in the terrane assembly of Trinidad and E. Venezuela. *Proceedings Petroleum Systems of Deep-water Basins: Global and Gulf of Mexico Experience: GCSSEPM Foundation, 21st Annual Research Conference, Transactions*, 159–192.

———, 2007. Cenozoic kinematics and dynamics of oblique collision between two convergent plate margins: the Caribbean-South America collision in eastern Venezuela, Trinidad and Barbados. *Transactions of GCSSEPM 27th Annual Bob F. Perkins Research Conference*, 458–553.

PINDELL, J. L., KENNAN, , WRIGHT, D., and ERIKSON, J. P., 2009. Clastic domains of sandstones in central/eastern Venezuela, Trinidad, and Barbados: Heavy mineral and tectonic constraints on provenance and palaeogeography. *Geological Society London Special Publications,* 328: 743–797.

POAG, C. W., 2015. Benthic Foraminifera of the Gulf of Mexico: Distribution, Ecology, Paleoecology. *College Station, Texas A & M University Press, Harte Research Institute for Gulf of Mexico Studies Series*, 239 pp.

PREECE, R. A., 1999. The physiological response of equatorial Neogene bathyal benthic foraminifera to low oxygen conditions. Unpublished Ph.D. thesis, University of London, 375 pp + 84 pls.

RATHBURN, A. E., LEVIN, L. A., HELD, Z., and LOHMANN, K. C., 2000. Benthic foraminifera associated with cold methane seeps on the northern California margin: Ecology and stable isotopic composition. *Marine Micropaleontology,* 38: 247–266.

RENZ, H. H., 1942. Stratigraphy of northern South America, Trinidad, and Barbados. *Proceedings of the 8th American Scientific Congress, 1940,* 4: 513–571.

———, 1948. Stratigraphy and fauna of the Agua Salada Group, State of Falcón, Venezuela. *Geological Society of America Memoir,* 32: 1–219.

REUSS, A. E., 1851. Über die fossilen Foraminiferen und Entomostraceen der Septarianthone der Umgegend von Berlin. *Deutche Geologische Gesellschaft, Zeitschrift, Berlin,* 3, 49–91.

ROHR, G. M., 1990. Paleogeographic maps, Maturin Basin of E. Venezuela and Trinidad. *Annual convention and exposition of the American Association of Petroleum Geologists, San Francisco, California, USA,* 3-6 June 1990.

ROURE, F. M., 2007. *Thrustbelts and Foreland Basins: From Fold Kinematics to Hydrocarbon Systems*. Springer, Berlin, Germany, 492 pp.

SALAZAR, M., MOSCARDELLI, L., FISHER, W., and LORENTE, M. A., 2011. Tectonostratigraphic evolution of the Morichito piggyback basin, Eastern Venezuelan Basin. *Marine and Petroleum Geology,* 28: 109–125.

SANCHEZ-VILLAGRA, M. R., AGUILERA, O. A. and CARLINI, A. A., 2010. *Urumaco and Venezuelan Paleontology: The Fossil Record of the Northern Neotropics*. Bloomington Indiana University Press, USA, 304 pp.

SAUNDERS, J. B., 1957. Trochamminidae and certain Lituolidae (Foraminifera) from the Recent brackish-water sediments of Trinidad, British West Indies. *Smithsonian Miscellaneous Collections* 134 (5): 1–16.

———, 1998. *Geological Map of Trinidad, with explanatory notes for 1997 Geological Map by J.B. Saunders, and H.C. Potter*. Ministry of Energy and Energy Industries, Government of the Republic of Trinidad and Tobago.

SCHNITKER, D., MAYER, L. M. and NORTON, S., 1980. Loss of calcareous microfossils from sediments through gypsum formation. *Marine Geology,* 36: 35–44.

SCHOTT, F. A., FISCHER, J., and STRAMMA, L., 1998. Transports and pathways of the upper-layer circulation in the western tropical Atlantic. *Journal of Physical Oceanography,* 28: 1904–1928.

SCHUBERT, R. J., 1902. Neue und interessante Foraminiferen aus dem südtiroler Altteriär. *Beiträge zur Paläontologie und Geologie Österreich-Ungarns und des Orients,* 14, 9–26.

SEN GUPTA, B. K., LOBEGEIER, M. K., and SMITH, L. E., 2009. Foraminiferal communities of bathyal hydrocarbon seeps, northern Gulf of Mexico: A taxonomic, ecologic, and geologic study. *U.S.Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS* 2009–013, 1–385.

SIESSER, W. G. and ROGERS, J., 1976. Authigenic pyrite and gypsum in South West African continental slope sediments. *Sedimentology,* 23: 567–577.

SMITH, G. A., 2000. Recognition and significance of streamflow-dominated piedmont facies in extensional basins. *Basin Research,* 12: 399–411.

STAINFORTH, R. M. S., 1948. Description, correlation, and paleoecology of Tertiary Cipero Marl Formation, Trinidad, B. W. I. *American Association of Petroleum Geologists, Bulletin,* 32: 1292–1330.

———, Ecology of arenaceous foraminifera. *The Micropaleontologist*, 6: 42–44.

———, 1968. Mid-Tertiary diastrophism in northern South America. In: Saunders, J.B., Ed., *4th Caribbean Geological Conference: Port of Spain, Trinidad*, 159–174.

SUTER, H. H., 1951. The general and economic geology of Trinidad, B. W. I. *Colonial Geology and Mineral Resources,* 2: 271–307.

VAN VLIET-LANOE, B., 2007. The autocyclic nature of glaciations. *Bulletin de la Société Geologique de France,* 178: 247–262.

VERGARA, L., RODRÍGUEZ, G. and MARTINEZ, I., 1997. Agglutinated Foraminifera and Sequence Stratigraphy from the Chipaque Formation (Upper Cretaceous) of El Crucero Section, Colombia, South America. *Micropaleontology,* 43: 185–201.

VILLAMIL, T., 1999. Campanian–Miocene tectonostratigraphy, depocenter evolution and basin development of Colombia and western Venezuela. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 153: 239–275.

VINCENT, H., WACH, G., and KETANNAH, Y., 2014. Heavy mineral record of Andean uplift and changing sediment sources across the NE margin of South America: a case study from Trinidad and Barbados. *Geological Society, London, Special Publications,* 386: 217–241.

WALL, G. P. and SAWKINS, J. G., 1860. Report on the Geology of Trinidad. Part I of the West Indian Survey. *Memoir of the Geological Survey*, 1–211.

WHEELER, C. B., 1963. Oligocene and Lower Miocene Stratigraphy of Western and Northeastern Falcon Basin, Venezuela. *American Assciation of Petroleum Geologists Bulletin,* 47: 35–68.

WILSON, B., 2003. Foraminifera and paleodepths in a section of the Early to Middle Miocene Brasso Formation, Central Trinidad. *Caribbean Journal of Science,* 39: 209–214.

———, 2004. Benthonic foraminiferal paleoecology across a transgressive-regressive cycle in the Brasso Formation (Early-Middle Miocene) of Central Trinidad. *Caribbean Journal of Science,* 40: 126–138.

———, 2005. Planktonic foraminiferal biostratigraphy and paleo-ecology of the Brasso Formation (Middle Miocene) at St. Fabien Quarry, Trinidad, West Indies. *Caribbean Journal of Science,* 41: 797–803.

———, 2007. Benthonic foraminiferal paleoecology of the Brasso Formation (*Globorotalia fohsi lobata* and *Globorotalia fohsi robusta* [N11-N12] Zones), Trinidad, West Indies: A transect through an oxygen minimum zone. *Journal of South American Earth Sciences,* 23: 91–98.

———, 2008a. Benthonic foraminiferal paleoecology indicates an oxygen minimum zone and an allochthonous, inner neritic assemblage in the Brasso Formation (Middle Miocene) at St. Fabien Quarry, Trinidad, West Indies. *Caribbean Journal of Science,* 44: 228–235.

———, 2008b. Using SHEBI (SHE Analysis for Biozone Identification): to proceed from the top down or the bottom up? A discussion using two miocene foraminiferal successions from Trinidad, West Indies. *Palaios,* 23: 636–644.

———, 2010. A lagoonal interlude with occasional hypersalinity in the deposition of the Early–Middle Miocene Brasso Formation of Trinidad. *Journal of South American Earth Sciences*, 29: 254–261.

———, 2012. Planktonic Foraminifera in the Early to Middle Miocene 'Lower Concord Calcareous Silt Member' at Mayo Quarry, Central Trinidad, and the invalidity of the Tamana Formation. *Newsletters on Stratigraphy,* 45: 105–114.

WILSON, B., COIMBRA, J. C. and HAYEK, L. C., 2014. Ostracoda (Arthropoda, Crustacea) in a Miocene oxygen minimum zone, Trinidad, West Indies: A test of the Platycopid Signal Hypothesis. *Journal of South American Earth Sciences,* 54: 210–216.

WILSON, B., FARFAN, P., and HUGHES, C., 2017. The formation placement and palaeoenvironment of the Middle Miocene Los Atajos Member, Trinidad. *Journal of South American Earth Sciences,* 76: 63–70.

WILSON, B., and HAYEK, L. C., 2014a. Ontology confounds reproducibility in ecology and climate science. *Life: The Excitement of Biology,* 2: 13–30.

———, 2014b. Foraminifera on the Demerara Rise offshore Surinam: crustal subsidence or shallowing of an oxygen minimum zone? *Geological Magazine,* 152: 788–801.

———, 2015. Distinguishing relative specialist and generalist species in the fossil record. *Marine Micropaleontology,* 119: 7–16.

WILSON, B., MILLER, K., THOMAS, A.-L., COOKE, N., and RAMSINGH, R., 2008. Foraminifera in the Mangal at the Caroni Swamp, Trinidad: Diversity, Population Structure and Relation to Sea Level. *Journal of Foraminiferal Research,* 38: 127–136.

WILSON, B. and VINCENT, H., 2014. Benthonic foraminifera in the Upper Miocene Cruse Formation at Quinam Bay, Trinidad, western tropical Atlantic Ocean, and their palaeoenvironmental significance. *Geological Magazine,* 151: 550–558.

Supplementary Data

Supplementary Data 1. Foraminifera of the interfingering Nariva and Cipero Formations at the Stripy Exposure.

Supplementary Data 2. Foraminifera from the other exposures analyzed.